Morphology and Pattern of Quaternary Sedimentation in the North Sea Basin (52-62°N)

Ottesen, D.[1], Batchelor, C.L.[2], Dowdeswell, J.A.[2], Løseth, H.[3]

[1] Geological Survey of Norway (NGU), Postboks 6315 Sluppen, Trondheim, N-7491, Norway; [2]Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK; [3]Statoil, Arkitekt Ebbels vei, 7053, Ranheim, Norway.

Abstract

The Quaternary North Sea Basin, which extends from northwest mainland Europe in the south (52°N) to the Norwegian Sea in the north (62°N), contains a thick (up to 1 km) sedimentary succession that records the changing nature of sediment supply from surrounding land areas during the last *c.*2.6 Ma. We use an extensive 2D and 3D seismic database to correlate major Quaternary seismo-stratigraphic surfaces and units across the North Sea and reconstruct the broad-scale infill pattern of the entire Quaternary North Sea Basin. The total volume of Quaternary sediments in the North Sea (350,000 km^2) is *c.*140,000 km^3, while the area inside the 500 m contour of the base-Quaternary surface has a volume of 109,000 km^3. Two largely independent depocentres developed in the North Sea Basin during the early Quaternary: the southern and central sub-basin was infilled by shelf fluvio-deltaic and prodeltaic sediments delivered from the east and south-east, whilst the northern sub-basin was infilled mainly by prograding glacigenic debris-flows deposited from an ice mass centred on the Norwegian mainland. Contour currents were an important mechanism of sediment deposition and reworking, with water circulation in the basin probably occurring in an anti-clockwise direction. Whilst most of the southern North Sea Basin was infilled by around 1.6-1.7 Ma, a depression persisted in the central North Sea until around 1 Ma. The analysis of landforms on 3D seismic data suggests that the Fennoscandian Ice Sheet (FIS) extended intermittently to the palaeo-shelf break in the northern North Sea during the earliest Quaternary and expanded into the central North Sea prior to the excavation of the Norwegian Channel.

1. Introduction

The North Sea, between the United Kingdom (UK), Scandinavia and continental North-West Europe (Fig. 1a), is a basin that has received sediments through most of the Cenozoic Era (the last 65 Ma; Nøttvedt et al., 1995; Fyfe et al., 2003; Gabrielsen et al., 2010; Knox et al., 2010). The morphology of the North Sea Basin was influenced structurally by the presence of the Viking and Central grabens, which have their axes above or slightly east of the center of the study area. Subsidence has taken place along the axis of the basin, together with uplift of the surrounding land areas and shallow shelf (e.g. the East Shetland Platform). This has enabled the development of a thick (up to 1 km) Quaternary succession within the North Sea Basin, which contains a record of the changing source, nature and rate of sediment supply from Scandinavia, North-West Europe and the UK during the last *c.* 2.6 Ma (Overeem et al., 2001; Anell et al., 2010; Goledowski et al., 2012; Gibbard and Lewin, 2016). The Quaternary sediments that are preserved within the North Sea Basin contain important information about past environmental conditions, including the timing and magnitude of ice-sheet build-up and decay, the changing configuration and efficiency of adjacent fluvial systems, and the varying intensity of ocean currents (Rose et al., 2001; Clark et al., 2004; Kuhlmann and Wong, 2008; Knox et al., 2010; Stuart and Huuse, 2012; Ottesen et al., 2014; Bridgland et al., 2015; Gibbard and Cohen, 2015; Lamb et al., 2017).

The geology of the North Sea Basin has been examined mainly within the boundaries of the surrounding nations, including the UK, Norway, Denmark, the Netherlands and Germany, and/or with a focus on either the southern, central or northern part of the basin (Fig. 1a) (Kuhlmann and Wong, 2008; Knox et al., 2010; Lamb et al., 2016). As a result, the morphology and infill history of the North Sea Basin has seldom been investigated on a broad-scale basis as a single entity (Anell et al., 2010; Rea et al., 2018). Many recent publications on the North Sea (e.g. Graham et al., 2011; Stewart et al., 2013; Westaway, 2017) still rely on maps of Quaternary sediment thickness that date back to the 1970s (Caston, 1977), further demonstrating the need for such an integrated compilation.

This study utilises an extensive database of two-dimensional (2D) and three-dimensional (3D) seismic data to produce new maps of the morphology and sedimentary infill of the entire North Sea Basin for several of the major stratigraphic units of the Quaternary, with a particular focus on the early Quaternary (2.6-0.8 Ma). Our seismic data extend from the coast of the Netherlands in the south (52°N) to the Norwegian Sea in the north (62°N) – a distance of approximately 1,100 km and an area of about 350,000 km^2 (Fig. 1b).

In this paper, we provide an overview of units and features described in previous works and estimate the sediment volumes and relative timing of the infill of the southern, central and northern sub-basins. This basin-wide analysis enables us to examine the changing sediment sources and significance of glacial, fluvial and oceanographic influences on sediment delivery to the entire basin through the Quaternary.

An important part of this work involves linking and merging the stratigraphies that have been developed, often independently, for the Norwegian, British, Dutch, German and Danish sectors of the North Sea (Cameron et al., 1992; Sørensen and Michelsen, 1995; Rijsdijk et al., 2005; Kuhlmann et al., 2006; Nielsen et al., 2007; Anell et al., 2010; Stoker et al., 2011; Ottesen et al., 2014; Thöle et al., 2014). This analysis builds on the work of Ottesen et al. (2014) and Kuhlmann and Wong (2008) by correlating major stratigraphic units across the entire North Sea Basin. Throughout this contribution, we use terminology that divides the North Sea into southern (south of 56°N), central (56-59°N) and northern (59-62°N) areas (Fig. 1a).

2. Background

2.1 Geological setting

The North Sea is a failed rift basin that formed by lithospheric extension during the late Palaeozoic and Mesozoic (Ziegler, 1990; Faleide et al., 2002). Thermal subsidence related to opening of the North Atlantic ceased by the start of the Cenozoic, forming an epicontinental basin into which up to 3 km of Cenozoic sediments have been deposited (Jordt et al., 1995; Michelsen et al., 1995; Anell et al., 2010; Knox et al., 2010). Episodes of basin inversion during the Cenozoic generated regional unconformities within some parts of the basin, including the Dutch and Danish sectors (Ziegler, 1992; White and Lovell, 1997). The most widely accepted model of Cenozoic sedimentation suggests that deltaic bodies of sediment prograded into the North Sea Basin from a source area that shifted gradually clockwise; from the north and northwest in the mid-Cenozoic, to the east and southeast by the early Quaternary (Cameron et al., 1993; Sørensen and Michelsen, 1995; Huuse et al., 2001; Overeem et al., 2001). However, it is recognised that sediments were continuously supplied, at varying rates, from the East Shetland Platform and Fennoscandia throughout the Cenozoic (Stewart, 1987; Galloway et al., 1993; Jordt et al., 1995; Anell et al., 2012; Eidvin et al., 2013).

Sediment deposition into the basin continued during the Miocene and Pliocene, forming a series of prograding sedimentary wedges (Eidvin and Rundberg, 2001; Fyfe et al., 2003; Rasmussen et al., 2005; Thöle et al., 2014). Late Cenozoic uplift of the East Shetland Platform led to the formation of several laterally extensive sand accumulations in the northern North Sea, including the Utsira Formation of late Miocene to Pliocene age, which is interpreted to have been formed by high-energy marine currents (Galloway, 2002; Eidvin and Rundberg, 2007; Gregersen and Johannessen, 2007; De Schepper and Mangerud, 2017). A regional hiatus, possibly produced by erosive debris flows, has been reported to exist above the Utsira Formation (Eidvin et al., 2013). This hiatus has been suggested to span c. 4.5 – 2.7 Ma (King, 1983, 1989; Eidvin et al., 2013), although new age assignments propose that the Utsira Formation may be significantly younger (De Schepper and Mangerud, 2017). The Utsira Formation immediately underlies the Quaternary sediments of the northern North Sea that are investigated in this study (Fig. 2).

In the central North Sea, Quaternary sediments are underlain by a condensed Upper Pliocene unit (Head et al., 2004; Eidvin et al., 2013). Miocene and Pliocene sedimentation in the southern North Sea was dominated by a westward prograding depositional style with sediments sourced mainly from the former Baltic (Eridanos) and Rhine-Meuse river systems, which continued to supply sediment to the basin through the early Quaternary (Bijlsma, 1981; Gibbard, 1988; Cameron et al., 1992; Overeem et al., 2001; Kuhlmann and Wong, 2008; Rasmussen et al., 2010; Olivarius et al., 2014; Thöle et al., 2014; Lamb et al., 2017). Quaternary sediments in the southern North Sea downlap onto a prominent Mid-Miocene Unconformity (Fig. 2).

The thick (up to 1 km) succession of Quaternary sediments in the North Sea Basin provides a record of the changing patterns and processes of sediment delivery to the basin through the past *c*.2.6 Ma (Anell et al., 2010; Knox et al., 2010; Ottesen et al., 2014; Lamb et al., 2017). Subsidence of the North Sea Basin and uplift along its British, European and Scandinavian margins, caused in part by extensive erosion of the land areas surrounding the basin, took place throughout the Quaternary (Riis, 1996; Faleide et al., 2002; Rasmussen et al., 2005; Gibbard and Lewin, 2016; Westaway, 2017; Lee et al., 2018).

2.2 Previous mapping of the Quaternary North Sea Basin

In previous mapping studies, the Quaternary infill of the North Sea Basin was mainly investigated within national boundaries (e.g. Cameron et al., 1992; Sørensen et al., 1997; Nielsen et al., 2007; Kuhlmann and Wong, 2008; Stoker et al., 2011; Goledowski et al., 2012) or with a focus on either the northern, central or southern areas of the basin (Fig. 1a) (Knutz, 2010; Ottesen et al., 2014; Lamb et al., 2017).

2.2.1 British sector

The British sector of the North Sea covers the western side of the northern, central and southern basin (Fig. 1a). The Quaternary sediments and stratigraphy of the British sector were investigated during the British Geological Survey's mapping campaign from the 1970s to the 1990s. Although this mapping campaign revealed important information about the nature of Quaternary sediments in the basin, the use of single-channel analogue seismic records presented problems in interpreting the seismic stratigraphy beneath the first seafloor multiple, leading to uncertainties about the location of the base-Quaternary boundary and the thickness of the Quaternary infill (e.g. Caston, 1977; Cameron et al., 1992; Johnson et al., 1993; Gatliff et al., 1994).

The early Quaternary sediments of the British sector of the North Sea, which are mainly fluvio-deltaic to marine, correspond with the Deltaic Division of the southern basin (Cameron et al., 1992) and the Aberdeen Ground and Shackleton formations of the Zulu Group of the central and northern basins, respectively (Fig. 2) (Johnson et al., 1993; Gatliff et al., 1994; Stoker et al., 2011). From around 0.7 Ma in the northern basin and around MIS 12 (*c.* 0.5 Ma) in the central and southern basin, a non-deltaic sediment unit records more extensive glaciation; these sediments include widespread glacial erosion surfaces, till deposition, and tunnel-valley development during several episodes of basin-wide glaciation (Cameron et al., 1987, 1992; Johnson et al., 1993; Gatliff et al., 1994).

Recent work on the Forties Field in the central British sector of the basin presents a new stratigraphy that distinguishes between the early Quaternary Upper Nordland Group Sequence and the Aberdeen Ground Formation of between around 1 and 0.5 Ma (Buckley, 2016; Vaughan-Hirsch and Phillips, 2017). In this interpretation, the Upper Nordland Group Sequence and the Aberdeen Ground Formation are separated by a glacigenic sequence (Crenulate Marker) that is characterised by glacial erosion and the presence of mega-scale glacial lineations (Buckley, 2012, 2016; Rose et al., 2016).

2.2.2 Norwegian sector

Few regional studies have investigated the entire Quaternary sequence in the Norwegian sector of the North Sea Basin (e.g. Jordt et al., 1995; Ottesen et al., 2014). Goledowski et al. (2012) used 2D seismic reflection profiles and well data to map the thickness of the

Quaternary package in the Norwegian sector. However, this study had no seismic coverage from the British sector, which contains a large part of the sediments of the central North Sea Basin (Fig. 1a).

Recent work by Ottesen et al. (2014) benefitted from access to an extensive database of seismic-reflection data covering both the Norwegian and British sectors of the basin north of 56°N. This study used 2D and 3D seismic data, calibrated using biostratigraphic analyses from several wells (Eidvin et al., 1999, 2013; Eidvin and Rundberg, 2007), to develop an informal seismic-stratigraphy for early Quaternary sediments in the central and northern North Sea Basin (Fig. 2). The clinoforms in the northern basin prograde in a westerly and northwesterly direction from the Norwegian mainland and contain elongate lobes that are interpreted as glacigenic debris-flows (Ottesen et al., 2014). The central North Sea Basin was infilled by generally fine-grained sediments from the southeast and east, suggesting a distal fluvial or glacifluvial origin.

2.2.3 Southern sectors

The southern North Sea Basin comprises the Dutch, German and Danish sectors, together with the southern part of the British sector to the west (Fig. 1a). Most of the infill of the German and Danish sectors of the basin occurred prior to the onset of the Quaternary (Rasmussen et al., 2005; Nielsen et al., 2007; Thøle et al., 2014). The traditional model is that a large component of this fill was sourced from the Baltic (Eridanos) river system, which fed a large delta at the eastern side of the basin during the Mid/Late Miocene, Pliocene and Quaternary (Bijlsma, 1981; Gibbard, 1988; Funnell, 1996; Overeem et al., 2001; Thøle et al., 2014; Gibbard and Lewin, 2016). An alternative model, in which a significant portion of these sediments was transported into the basin from river systems in Scandinavia, has been proposed based on studies of the provenance and age of detrital zircon grains in Miocene sands in Denmark (Rasmussen et al., 2010; Olivarius et al., 2014).

A thicker sequence of Quaternary sediments is preserved in the Dutch sector of the southern North Sea (Rijsdijk et al., 2005; Stuart and Huuse, 2012). Sørensen et al. (1997) used seismic data from the Dutch, German and Danish sectors to define 31 seismic sequences and nine composite sequences of Miocene to Quaternary age. The uppermost composite sequences, VI to IX, span the early Quaternary and are composed of deltaic sediment (Fig. 2). This study was built upon by Kuhlmann and Wong (2008), who used biostratigraphy and palaeomagnetic data, combined with 3D seismic data, to define 13 seismic sequences of Miocene to Quaternary age within the Dutch sector of the North Sea. The base-Quaternary, of around 2.6 Ma, was interpreted to be located at the transition between sequences 4 and 5 (Fig. 2). Most of the Dutch sector of the southern North Sea Basin is inferred to have been infilled by around 1.8 Ma (Fig.2) (Kuhlmann and Wong, 2008; Stuart and Huuse, 2012; Lamb et al., 2017).

2.2.4 Basin-wide compilations

Some studies have mapped the base-Quaternary across more than one sector of the North Sea Basin. Knox et al. (2010), Lamb et al. (2017) and Arfai et al. (2018) mapped the base-Quaternary surface for the southern and central part of the basin, whilst Rea et al. (2018) have correlated between the northern and southern parts of the basin. Thickness maps for the entire North Sea have been compiled by Anell et al. (2010, 2012), although these focussed on basin morphology and long-term patterns of sedimentation through the Cenozoic.

3. Data and methods

An extensive database of 2D and 3D seismic data (Fig. 1b) is used to correlate major Quaternary seismo-stratigraphic surfaces and sequences across the different sectors of the North Sea Basin. Our interpretations are based on those of several authors (e.g. Sørensen and Michelsen, 1995; Sørensen et al., 1997; Eidvin et al., 1999; Kuhlmann et al., 2006; Kuhlmann and Wong, 2008; Nielsen et al., 2007; Knox et al., 2010; Haavik and Landrø, 2014; Ottesen et al., 2014), which, combined with the analysis of newly-available seismic data, are compiled to investigate the geological development of the entire North Sea Basin (52-62°N).

The seismic database includes high-quality regional 2D profiles (Fig. 1b), which aid stratigraphic correlation between sectors of the North Sea and the production of maps of the regional infill pattern. The North Sea Renaissance (NSR) lines, which cover parts of the British and Norwegian shelves, were accessed from TGS Geophysical Company or Statoil's seismic database. These data have a vertical resolution of about 10 to 15 m. Several regional 2D surveys have also been used in the Dutch, German and British sectors. In addition, we have access to three large 3D seismic cubes (Fig. 1b). The availability of a large number of new seismic-reflection profiles enables us to improve the maps that were presented in Ottesen et al. (2014) by extending our interpretations into the southern North Sea. It should be recognised, however, that the spacing between seismic profiles is wider in the south compared with the dense grid of 2D and 3D seismic data in the central and northern basins (Fig. 1b).

This work enables the major horizons and stratigraphic sequences of the Quaternary sediments in the North Sea to be mapped across the entire basin (Figs. 3 and 4). Establishing a chronology of these internal Quaternary surfaces is challenging: however, we prefer to give the surfaces tentative ages, accepting that the absolute chronology associated with the North Sea stratigraphy is likely to be refined by succeeding work. Horizontal time slices and seismic amplitude maps were used to identify and interpret subdued glacial landforms on palaeo-shelf and slope surfaces. A velocity of 1800 m/s is used for depth conversion of the time surfaces, which is derived from a simple velocity model based on velocity measurements in exploration wells in the North Sea (Ottesen et al., 2014). We note that, due to subsidence of the sediments within the North Sea, our maps of surface depth and unit thickness should not be used as former water depths. Palaeo-water depths can be estimated from the height of buried clinoforms within the basin stratigraphy.

4. Results: Broad-scale morphology and infill of the North Sea Basin

The maps presented in Figures 3 and 4 show the morphology and sedimentary infill of the North Sea Basin for three major stratigraphic surfaces and three major units of the Quaternary. The suggested ages of these surfaces, together with the correlation of several independent stratigraphies across the basin, are shown in Figure 2.

4.1 Basin morphology at the start of the Quaternary

The base-Quaternary stratigraphic surface in the southern North Sea (Fig. 3a) is established at the base of Sequence 5 of Kuhlmann and Wong (2008) in the Dutch sector, which has been dated to *c.* 2.6 Ma using palaeomagnetic and biostratigraphic data (Kuhlmann et al., 2006) (Fig. 2). We correlated this horizon northwards into the central North Sea Basin and joined it with the base of the Naust Formation of the northern North Sea and mid-Norwegian shelf, which is dated to slightly less than 2.75 Ma (Eidvin et al., 1999, 2013; Dahlgren et al., 2002; Rise et al., 2005; Ottesen et al., 2009, 2014). Whereas the base-Quaternary in the northern North Sea is represented by a downlap surface that separates the late Miocene to early Pliocene Utsira Sands from overlying glacially influenced sediments, the deltaic sediments of Miocene to Quaternary age in the southern basin downlap westwards onto the mid-Miocene unconformity (Kuhlmann and Wong, 2008; Thøle et al., 2014).

The maps presented in this study incorporate a slightly revised version of the base-Quaternary horizon described in Ottesen et al. (2014). Using newly available seismic data, we show that the base-Quaternary was too high in the package when compared with the seismo-stratigraphic work of Sørensen and Michelsen (1995) on the Danish shelf and the revised chronological control of Kuhlmann et al. (2006) in the Dutch sector. The reinterpretation of the depth position of the base-Quaternary horizon in this study affects only a small part of the North Sea Basin. The most significant difference is in the central and eastern parts of the central basin, where the base-Quaternary is reinterpreted to be 200-300 ms deeper in the southernmost part of the Norwegian sector and up to 200 ms deeper on the British side. Whereas Ottesen et al. (2014) located the base-Quaternary at approximately 700 m depth in well 2/4-14, our revised interpretation is in agreement with the base-Quaternary horizons of Eidvin et al. (1999, 2013) and Haavik and Landrø (2014), which are located at depths of 980 m and 950 m, respectively.

The broad-scale shape of the North Sea Basin at the beginning of the Quaternary (Fig. 3a) largely reflects the structural form of the underlying Central and Viking grabens of Mesozoic age. It should be noted that the geometry of the base-Quaternary surface has been altered by continuous subsidence along the basin axis as well as uplift of the surrounding land areas due to isostatic compensation (denudational isostacy) and compaction during the last *c.* 2.6 Ma (Riis, 1996; Stuevold and Eldholm, 1996; Rasmussen et al., 2005; Westaway, 2017; Arfai et al. 2018; Lee et al., 2018).

The morphology of the North Sea Basin at the beginning of the Quaternary was dominated by two deep depressions that provided accommodation space for sediment input from the surrounding land areas (Fig. 3a). The southern depression, which spans the southern and central North Sea and extends underneath part of the present-day land area of the Netherlands (Rijsdijk et al., 2005), is elongate in a NNW-SSE direction and reaches a maximum depth of around 1,220 ms (1100 m) between 56°N and 57°N. This is in agreement with other reconstructions of the base-Quaternary surface in the southern and central North Sea (Knox et al., 2010; Lamb et al., 2017). The depth of the base-Quaternary in the North Sea shows that the basin experienced fast subsidence during the last 2.6 Ma. The majority of this subsidence is probably a consequence of compaction and load-induced subsidence, with a smaller proportion possibly caused by post-glacial collapse, local lower crustal flow and/or dynamic topography (Kooi et al., 1991; Anell et al., 2010; Westaway, 2017; Arfai et al., 2018). A northern depression continues into the northern North Sea to the Norwegian Sea (Ottesen et al., 2014) (Fig. 3a). The two depressions, which are termed the southern and central sub-basin, and the northern sub-basin, respectively, are separated by a NE-SW-trending shallower and narrower region around 59°N, where the East Shetland Platform extends far east.

4.2 Top of Unit B surface

The top of Unit B surface, which is a high-amplitude reflector in the northern North Sea Basin (Ottesen et al., 2014), is extended into the central and southern areas of the North Sea (Figs. 2 and 3b). In the central North Sea, this horizon occurs close to but below the top of Clinoform Unit 1 (Fig. 2). In the southern North Sea, the top of Unit B is shown to be slightly younger than the upper reflector of Sequence 13 of Kuhlmann and Wong (2008), which is suggested to correspond with the top of the Olduvai palaeo magnetic Subchron dated to about 1.8 Ma (Fig. 2). The top of Unit B surface shows that the southern North Sea Basin and the eastern margin of the northern North Sea Basin had been entirely or almost entirely infilled by around 1.6-1.7 Ma (Kuhlmann and Wong, 2008) (Fig. 3b). Deep sub-basins continued to exist in the central North Sea and in the northwest northern North Sea (Fig. 3b).

4.3 Upper Regional Unconformity

On the eastern side of the northern North Sea Basin, a prominent URU has been linked to the formation of the Norwegian Channel by the Norwegian Channel Ice Stream. The URU was formed during several episodes of glacial erosion, with initial incision of the Norwegian Channel probably occurring sometime close to the early-middle Quaternary boundary (Sejrup et al., 1995, 2003; Stoker et al., 2005). This event has been dated to after around 1.1 Ma, based on amino-acids, micropalaeontological and palaeomagnetic analysis of glacial and related sediments in a cored geotechnical borehole close to the Troll Field, in which a till, called the Fedje Till, was recorded at the base of the Norwegian Channel (Sejrup et al., 1995, 2000). It has, alternatively, been suggested that initial initiation of the Norwegian Channel Ice Stream occurred later than 1.1 Ma, around or slightly younger than 0.8 Ma (Ottesen et al., 2014). Although it has not been possible to correlate the Brunhes-Matuyama magnetic reversal (0.78 Ma) from boreholes at the western side of the northern North Sea (Stoker et al., 1983) into the central parts of the basin, this palaeo magnetic boundary appears commonly to be located close to the URU horizon (Ottesen et al., 2014).

The URU is difficult to identify on the western side of the northern North Sea Basin where erosion by the Norwegian Channel Ice Stream did not take place. However, this boundary can be approximately defined by a shift from westward- to eastward-dipping clinoforms, which reflects a change in the direction of sediment delivery from a predominantly eastern source to one from the Shetland Platform to the west (Ottesen et al., 2014).

The term URU-equivalent is used to denote the conformable equivalent surfaces of the URU in the transitional area to the central and southern basins, without the implication of an unconformity to the west and the south of the Norwegian Channel. In the central North Sea Basin, we have mapped the URU to merge with the top of the sedimentary sequence that infilled the central basin from the east, southeast and south (i.e. the top of the Upper Central Basin Unit (Fig. 7). In this study, the URU-equivalent surface of the central basin is extended southwards into the southern North Sea, where it is merged with a prominent erosional unconformity (Moreau et al., 2012), as shown in Figure 5. The URU and URU-equivalent surface used in this study is therefore time-transgressive across the North Sea Basin, being older in the northern and central basin (around 1 Ma) and younger (possibly as young as 0.5 Ma) in the southern basin where it merges with the glacigenic unconformity of Moreau et al. (2012). Several of the units that infill the central basin thin significantly and are not present in the southern North Sea Basin at the resolution of our seismic data (Figs. 5 to 7).

The map of the URU and URU-equivalent surface in Figure 3c shows the morphology of the North Sea Basin once the southern, central and northern basin areas have been infilled. A wide and shallow depression is still apparent in the centre of the central North Sea, even though the central basin has been infilled and the sediments that overlie the URU-equivalent surface are mainly flat-lying (Figs. 5 to 8). The palaeo-Norwegian Channel dominates the shape of the basin to the north and east of the study area (Fig. 3c).

4.4 Present-day seafloor

The present-day seafloor of the central and southern North Sea has limited relief, with a few subdued depressions and bathymetric highs, including the Witch Ground Basin and Dogger Bank (Fig. 3d). The central basin depression that was identified on the URU-equivalent surface (Fig. 3c) does not have any bathymetric expression on the seafloor of the central North Sea (Fig. 3d), indicating that it has been infilled.

The Norwegian Channel, which reaches depths of more than 700 m, is a prominent feature on the seafloor of the northern and eastern North Sea (Fig. 3d). In the far northeast of the study area, the eastern margin of the Norwegian Channel is around 60 km to the west of its former location beneath the Måløy Plateau (Fig. 3c).

4.5 Basin infill

The Quaternary sediments of the North Sea Basin are thickest along a NNW-SSE central axis, along which a maximum is reached around 56°N where accommodation space facilitated the deposition of around 1150 ms (1030 m) of sediment (Fig. 4a). A significant

Quaternary sedimentary depocentre, which reaches a thickness of up to 1800 ms (1600 m), is also present in the northern North Sea Basin, north of about 61°N (Fig. 4a).

The map of sediment thickness between the base-Quaternary surface and the top of Unit B surface (Fig. 4b) shows that two major depocentres, sourced from different regions of the basin flanks, developed in the North Sea during the first *c.*1 Ma of the early Quaternary; one in the southern and central sub-basin, and one in the northern sub-basin. The southern North Sea depocentre is thickest in the Dutch sector, where up to 600 ms (*c.* 540 m) of sediment was deposited between around 2.6 and 1.6-1.7 Ma (average sedimentation rate of up to 540 m/Ma). An independent depocentre is also present in the northern North Sea during the first *c.*1 Ma of the early Quaternary (Fig. 4b). This depocentre reaches a maximum thickness of around 525 ms (470 m) to the west of Sognefjorden. The eastern part of this depocentre appears to have been significantly thicker originally, prior to the middle Quaternary glacial carving of the Norwegian Channel. Comparatively little sediment fill (generally less than 100 ms (90 m)) occurred in the central North Sea Basin during the first c.1 Ma of the Quaternary (Fig. 4b).

The map in Figure 4c shows the sediment thickness between the top of the Unit B surface and the URU and URU-equivalent surface. In the southern and central sub-basin, this unit probably spans from around 1.6-1.7 Ma to as young as 0.5 Ma. Little sediment was deposited in the southern North Sea during this period, as a consequence of the prior infilling of available accommodation space (Kuhlmann and Wong, 2008). Instead, the focus of sediment delivery had shifted to the British sector of the central basin, where up to 970 ms (870 m) of sediments were deposited (average sedimentation rate of up to 790 m/Ma). In the northern North Sea, the focus of sediment delivery had shifted further north and west. This sediment infill probably occurred between around 1.6-1.7 Ma and 1 Ma, prior to the initiation of the Norwegian Channel Ice Stream.

The sediment thickness between the URU and URU-equivalent horizon and the present-day seafloor, which includes most of the middle to late Quaternary sediments of the North Sea, is shown in Figure 4d. These sediments reach up to 340 ms (300 m) in the central part of the central basin (average sedimentation rate of up to 600 m/Ma). Up to 400 ms (350 m) of sediments were deposited above the URU on Måløy Plateau during the last *c.* 1 Ma (Fig. 4d).

<u>4.6 Sediment volume calculations</u>

The total volume of Quaternary sediments in the North Sea (between 52°N - 62°N and 2°W - 7°E) is around 140,000 km^3. The area within the 500 m contour of the base-Quaternary surface (blue outline in Figs. 1a and 11), the Quaternary sediment volume is estimated as 109,000 km^3 (Table 1). Of this, around 88,000 km^3 and 21,000 km^3 is contained within the southern and central sub-basin and northern sub-basin, respectively. Our Quaternary sediment volume calculation for the southern and central sub-basin is similar to the infill volume estimated for this region by Lamb et al., 2017 (83,000 km^3). The sediments that are preserved between the top of Unit B surface and the URU and URU-equivalent surface (Fig. 4c) make up the majority of the sediment volume of the Quaternary North Sea Basin, with a smaller proportion of the total sediments contained within the base-Quaternary to top of Unit B interval (Fig. 4b) and the URU and URU-equivalent to seafloor interval (Fig. 4d) (Table 1).

Our sediment volume calculations (Table 1) do not include material that has been eroded and removed from the North Sea over the last *c.*2.6 Ma. Most notably, the North Sea trough-mouth fan (TMF), which extends beyond the northern limit of our study area into the Norwegian Sea (Fig. 1a), contains around 40,000 km^3 of sediment that was eroded and removed from the North Sea by the Norwegian Channel Ice Stream (Nygård et al., 2005; Hjelstuen et al., 2012).

5. Southern and central North Sea (52-59°N)

The mapping of major seismo-stratigraphic surfaces and units across the North Sea reveals that two largely independent depocentres developed in the North Sea Basin during the Quaternary: one in the southern and central sub-basin, and the other in the northern sub-basin (Figs. 3 and 4). In this section, we examine and review the basin morphology and patterns and processes of sedimentation in the southern and central sub-basin.

5.1 Seismic stratigraphy

The early Quaternary seismic sequences of Kuhlmann and Wong (2008) (Sequences 5 to 13) were correlated from the Dutch offshore sector northwards into the central North Sea (Figs. 5 to 7). These sequences, which have been inferred to span *c.* 2.6 to 1.8 Ma, are shown to be located entirely within Clinoform Unit 1 - the lowermost seismic unit of Ottesen et al. (2014) in the central North Sea (Figs. 2 and 5 to 7). The overlying central basin units (Clinoform Units 2 and 3, the Central Basin Unit, and the Upper Central Basin Unit), which are younger than 1.8 Ma, thin towards the south and are truncated by a prominent glacial unconformity in the southern North Sea (Fig. 5) (Moreau et al., 2012). To the northeast of the central basin, the top of Clinoform Unit 3 surface has an irregular character on seismic profiles and truncates underlying reflections (Fig. 7).

At roughly the same time that Clinoform Units 1, 2 and 3 were deposited in the eastern part of the central basin, an acoustically layered and mounded unit, termed Unit Z, was deposited along the western, British, side of the central basin (Figs. 2 and 11). This unit has been interpreted as a contourite deposit (Faugères et al., 1999; Ottesen et al., 2014) and its irregular upper surface is known as the Crenulate Marker (Fyfe et al., 2003; Buckley, 2016). The Crenulate Marker of the western central basin corresponds with the top of Clinoform Unit 3 surface in the eastern central basin (Fig. 2). Seismic correlation and data from well logs suggest that the Unit Z contourites developed during the early Quaternary, with the base-Quaternary located close to the base of Unit Z (Rundberg and Eidvin, 2005; Ottesen et al., 2014).

A relatively small (area of *c.*100 km²), east-northeast-prograding depocentre is identified at the western, British, side of the southern and central sub-basin at about 55°N (Fig. 11). This depocentre has been interpreted as a delta that was produced by rivers draining from the UK into the North Sea Basin during the early Quaternary.

The lower Quaternary sediments that infill the central basin are capped by the relatively flat-lying URU-equivalent surface, which is truncated by, and merged with, a prominent unconformity in the southern North Sea (Figs. 5 to 7). This unconformity corresponds to the glacigenic unconformity of Moreau et al. (2012), which has been suggested to have been produced by ice-sheet erosion during the middle Quaternary (Cameron et al., 1992). A complex stratigraphy of middle to late Quaternary sediments, which corresponds with the California and Reaper glacigenic groups of Stoker et al. (2011) (Fig. 2), overlies the URU-equivalent surface in the southern and central basin.

5.2 Pattern of basin fill

A NNW-SSE orientated, elongate depocentre, up to 640 ms (580 m) thick, developed in the Danish, German and Dutch sectors of the North Sea during the early Quaternary (Fig. 10a to d). This pattern of sediment fill is consistent with a large delta prograding into the eastern side of the basin during the early Quaternary (Bijlsma, 1981; Gibbard, 1988; Cameron et al., 1992; Funnell, 1996; Overeem et al., 2001; Anell et al., 2010; Kuhlmann and Wong, 2008). The focus of sediment deposition shifted westwards through the early Quaternary, with the Danish and German sectors becoming mostly infilled by around 1.8 Ma (Fig. 9d). At the beginning of the Quaternary, a small subsidiary basin, up to 700 ms (670 m) deep, was present in the Dutch sector of the North Sea to the southwest of the main basin (Fig. 9a).

Most of the infilling of this subsidiary basin took place between around 2 and 1.9 Ma (Fig. 10c).

The central North Sea Basin received comparatively little sediment fill during the first *c.*1 Ma of the Quaternary, between around 2.6 and 1.7 Ma, except for an area in the southwest corner of the Norwegian shelf (Fig. 10a to d). This pattern is probably a consequence of the greater distance of this region from the advancing delta front to the southeast. The depocentre in the Norwegian sector probably indicates that a source existed in southern Norway and the depocentre was filled in by fluvial or glacifluvial sediments. The British sector of the central basin became the focus of sediment delivery from around 1.8 Ma (Fig. 10e). By the top of Clinoform Unit 1 surface, which is younger than 1.8 Ma, the southern basin is infilled and a 180 km-wide depression that has been infilled by up to 1 s (900 m) of sediment remains in the central North Sea (Fig. 9e). This central depression, which is slightly elongate in a NNE-SSW direction, was infilled gradually during the second half of the early Quaternary, as represented by Clinoform Units 2 to 3, the Central Basin Unit and the Upper Central Basin Unit of Ottesen et al. (2014) (Fig. 10e to i). Accommodation space for the deposition of prograding sediment packages in the central North Sea (Clinoform Units 1 to 3) may have been provided by Late Pliocene to Early Pleistocene uplift of Norway (Rasmussen et al., 2010).

A 120 ms (110 m) deep depression is present on the upper surface of the Upper Central Basin Unit (Fig. 9i), which corresponds with the URU-equivalent surface. This depression may be a consequence of continuing subsidence of the central part of the central basin during the Quaternary. This region probably experienced greater compaction and load-induced subsidence (e.g. Arfai et al., 2018) compared with surrounding areas of the central and southern sub-basin that experienced less sediment infill during this time.

An overview of the infill pattern of the North Sea Basin, produced by mapping the 500 ms time contour for each seismic unit, is shown in Figure 11. This diagram reveals that, rather than being concentric, the infill pattern of the basin is skewed, maintaining a steeper slope to the west. This shows that the majority of the basin-fill sediment was delivered from the east and southeast side of the basin. With the exception of a relatively small delta and a contouritic unit (Fig. 11), the southern and central North Sea Basin received relatively little sediment input from the UK during the early Quaternary, especially prior to around 1.8 Ma. The discrepancy in sediment input is probably a consequence of the smaller drainage basin areas of British fluvial systems compared to the vast drainage networks of the European mainland and Scandinavia (Gibbard and Lewin, 2016). In addition, UK river systems probably lacked the sediment supply (as land surfaces were generally stabilised by vegetation) and the energy regime to transport coarse bedload into the basin in an effective manner during the Early Quaternary (Rose et al., 2001; Lee et al., 2018).

5.3 Processes of sedimentation in the southern and central North Sea Basin

The recent application of industry 3D seismic data has enabled the identification and interpretation of subdued landforms on palaeo-surfaces within the stratigraphy of the North Sea (Fig. 12) (Knutz, 2010; Stuart and Huuse, 2012; Dowdeswell and Ottesen, 2013, 2016; Buckley, 2016; Huuse and Kristensen, 2016; Lamb et al., 2016, 2017; Ottesen et al., 2014, 2016; Rose et al., 2016; Stewart, 2016; Reinardy et al., 2017; Rea et al., 2018). Five main landforms have been recognised within the Quaternary sediments of the southern and central sub-basin: delta-front subaqueous channels; slope-parallel mounded ridges; linear to curvilinear depressions; elongate lineations; and linear to sinuous wide channels.

Down-slope channels have been identified from 3D seismic data on the advancing delta front in the southern and central sub-basin (Knutz, 2010; Stuart and Huuse, 2012; Lamb et al., 2016). The channels are interpreted to have formed in a shelf-sea setting by erosional density-driven flows that transported deltaic sediment to deeper parts of the basin (Lamb et al., 2016). Some channels of similar morphology have a cross-slope orientation, suggesting that downslope flows may have been deflected by bottom currents that flowed parallel to the slope in an anticlockwise direction (Lamb et al., 2016).

Slope-parallel mounded ridges, interpreted as sand ridges formed by contour currents, have been identified from early Quaternary horizons on the mid- to lower delta slope (Kuhlmann and Wong, 2008; Stuart and Huuse, 2012). Similar ridges, which are up to 500 m wide and characterised by high-amplitude reflections, are identified in this study close to the transitional area between the central and northern basins (Fig. 12a). These landforms are interpreted to have been produced by contour currents that operated within the North Sea Basin during the early Quaternary.

Chaotically distributed linear to curvilinear depressions, up to several tens of kilometres long and several hundred metres wide, have been reported from horizons dated to older than 2 Ma in the southern and central North Sea (Kuhlmann and Wong, 2008; Knutz, 2010; Stuart and Huuse, 2012; Dowdeswell and Ottesen, 2013, 2016; Rea et al., 2018). These features are interpreted as iceberg ploughmarks that are produced by the grounding of iceberg keels on the seafloor (e.g. Woodworth-Lynas et al., 1991). In this study, we identify similar curvilinear scours, interpreted as iceberg ploughmarks, on horizons down to around 2 Ma in age (Fig. 12b).

Recently, multiple generations of faint northeast-southwest trending elongate lineations have been observed on 3D seismic data of the Crenulate Marker in the British sector of the central North Sea, at around 58°N (Fig. 2) (Buckley, 2012, 2016; Rose et al., 2016; Rea et al., 2018). These landforms have been interpreted as subglacially formed mega-scale glacial lineations that record the former pathway of a fast-flowing ice stream. Buckley (2016) dated some of these features to be close to the Jaramillo Sub-chron at 1 to 1.1 Ma, whilst Rea et al. (2018) assigned an estimated minimum age of 1.87 Ma to the oldest flowset of mega-scale glacial lineations in this region.

Seismic investigations of the flat-lying sediments that overlie the URU-equivalent surface in the central and southern sub-basin have revealed several generations of linear to sinuous wide (up to several km) channels (e.g. Fig. 12d) (Huuse and Lykke-Anderson, 2000; Praeg, 1996; Bradwell et al., 2008; Lutz et al., 2009; Graham et al., 2010, 2011; Moreau et al., 2012; van der Vegt et al., 2012; Stewart et al., 2013; Stewart, 2016). These features, which have undulating thalwegs and often display a cross-cutting pattern, are interpreted as tunnel valleys that were formed by meltwater erosion beneath a grounded ice sheet. Tunnel-valley incision is inferred to have occurred during several middle to late Quaternary glacial periods, including MIS 12, 6 and 2 (Stewart and Lonergan, 2011).

6. Northern North Sea (59-62°N)

In this section, we examine and review the Quaternary basin morphology and patterns and processes of sedimentation in the northern North Sea sub-basin.

6.1 Seismic stratigraphy

The seismic stratigraphy of Ottesen et al. (2014), which recognised four major clinoform units (A to D), is used to categorise the sediments of the northern North Sea (Figs. 2 and 8). Although there is a general lack of chronological control, Units A to C are interpreted to have been deposited during the early Quaternary, with Unit D encompassing the middle to late Quaternary sediments (Ottesen et al., 2014; Batchelor et al., 2017). The depocentre of the northern North Sea developed largely independently from the southern and central depocentre during the early Quaternary (Figs. 3 and 4). As such, Units A to D are not present south of around 59°N. Similarly, many of the seismic units that are recognised in the southern and central North Sea cannot be traced northwards of the narrow transition zone between the central and northern basins (Fig. 2).

It is, however, possible to map the upper reflection of Unit B across the study area (Fig. 3b), which enables the relative position of each unit to be determined (Fig. 2). Units A and B are shown to span a broadly similar time period to Sequences 5 to 13 of Kuhlmann and Wong (2008) in the southern North Sea (Fig. 2). The upper reflection of Unit B is slightly higher in the stratigraphy than the top of Sequence 13; we therefore suggest a tentative age of around 1.6-1.7 Ma for the top of Unit B surface (Fig. 2). The URU in the northern North Sea can be traced into the central North Sea, where we have linked it with the top of the Upper Central Basin Unit (Figs. 2 and 3c).

<u>6.2 Pattern of basin fill</u>

The geometry of Unit A, which follows the shape of the Norwegian coastline between 59°30´N and 61°30´N (Figs. 8 and 11), suggests that the early Quaternary sediments in the northern North Sea were sourced, at least in part, from an ice sheet that extended intermittently beyond the western Norwegian coastline (Ottesen et al., 2014). This source region corresponds with the location of several major present-day fjords, including the 200 km-long Sognefjorden system. The Unit B depocentre has similar geometry to Unit A, but is located further seaward due to the continued westerly progradation of the shelf break (Figs. 8 and 11). Units A and B, which were probably deposited during the first 1 Ma of the early Quaternary, between around 2.7 Ma and 1.6-1.7 Ma, reach a combined thickness of 520 ms (470 m).

At approximately the same time that Units A and B were deposited along the eastern side of the northern basin, a 150 ms-thick (130 m) delta developed at the western basin edge at around 60°N (Fig. 11) (Ottesen et al., 2014). Although this delta was probably fed by rivers that flowed across the East Shetland Platform in the British sector, the deltaic depocentre is located in the Norwegian sector of the northern sub-basin. As a consequence of sediment input from both the western and eastern basin sides during the early Quaternary, a narrow passageway existed between the northern and central North Sea (Figs. 3b and 11).

The easternmost part of the Shetland Drift contourite accumulation, which is of late Neogene to middle Quaternary age (Turrell et al., 1999; Knutz and Cartwright, 2003; Hohbein and Cartwright, 2006), is present along the continental slope at the northwestern edge of the study area (Fig. 11). A relatively thin (c. 50 m) unit that directly overlies the base-Quaternary surface in the northern North Sea has been interpreted as the south-east extension of the Shetland Drift (Batchelor et al., 2017) and as an extrusive sand body that came to the surface as a result of pressure build up from rapidly prograding shelf sediments (Løseth et al., 2012, 2013).

The remaining infill of the northern North Sea sub-basin comprises the sediments of Unit C, which are younger than around 1.6-1.7 Ma. These sediments are mainly derived from an ice sheet on the Norwegian mainland, but also contains a component of contourite deposition along the northeast basin margin (Fig. 8) (Batchelor et al., 2017). After the formation of the Norwegian Channel by the Norwegian Channel Ice Stream, the focus of sediment deposition is shifted into the Norwegian Sea, forming the Unit D depocentre that comprises most of the North Sea TMF (Figs. 8 and 11). The palaeo-Norwegian Channel initially extended beneath the Måløy Plateau (Fig. 3c), which is a relatively shallow region of the present-day continental shelf (Fig. 3d) (Rise et al., 2004; Batchelor et al., 2017). About 500 ms (450 m) of sediment was deposited above the URU on the Måløy Plateau during the last *c.*1 Ma (Fig. 4d).

6.3 Processes of sedimentation in the northern North Sea Basin

Three types of landform that have been identified in the southern and central sub-basin are also recognised from 3D seismic data in the northern North Sea stratigraphy: linear to curvilinear depressions; elongate lineations; and linear to sinuous wide channels.

Chaotic linear to curvilinear depressions, interpreted as iceberg ploughmarks, are identified on several palaeo-shelf surfaces in the northern North Sea. Whereas similar landforms are present on horizons down to around 2 Ma in age in the southern and central basin (Fig. 12b) (Kuhlmann and Wong, 2008; Knutz, 2010; Stuart and Huuse, 2012; Dowdeswell and Ottesen, 2013), the ploughmarks in the northern sub-basin are generally identified on middle and late Quaternary surfaces (Ottesen et al., 2014; Batchelor et al., 2017). This is interpreted to be a consequence of the erosion and removal of many palaeo-shelf surfaces in the northern North Sea by the Norwegian Channel Ice Stream (Dowdeswell et al., 2007).

In this study, we identify northeast-southwest orientated elongate ridges up to 20 km long from a 3D seismic cube west of Stavanger (Fig. 1b and 12c). The elongate ridges are identified from a horizontal time slice at 360 ms depth, which corresponds with the top of Clinoform Unit 3 surface (Figs. 2, 7 and 9g). At the eastern side of the central basin, the top of Clinoform Unit 3 surface has an irregular character and truncates underlying reflections; it is interpreted as a glacial erosion surface (Fig. 9g). The morphology and dimensions of the elongate ridges on the top of Clinoform Unit 3 surface (Fig. 12c) suggest that they are subglacially formed mega-scale glacial lineations that record the flow direction of fast-flowing ice (Stokes and Clark, 1999). The location and orientation of the mega-scale glacial lineations identified in this study corresponds closely with previously recognised elongate lineations in the Norwegian sector of the central basin, which have been tentatively dated to around 1.2 Ma (Reinardy et al., 2017), and on the Crenulate Marker (Fig. 2) and deepest parts of the central basin in the British sector of the central basin (Fig. 9g) (Buckley, 2012, 2016; Rose et al., 2016; Rea et al., 2018). Several generations of elongate ridges, interpreted as mega-scale glacial lineations, are also located on middle to late Quaternary horizons within the Norwegian Channel and beneath the present-day shallow bank of Måløy Plateau; they are interpreted to be related to the initial flow of the Norwegian Channel Ice Stream (Nygård et al., 2004; Rise et al., 2004, 2016; Batchelor et al., 2017).

Linear to sinuous wide channels, of similar dimensions and geometry to those described from the southern and central North Sea (Praeg, 2003; Lonergan et al., 2006; Stewart and Lonergan, 2011; Stewart et al., 2013; Stewart, 2016), have been recognised within middle to late Quaternary sediments in the Norwegian sector of the northern North Sea (Reinardy et al., 2017). These landforms are interpreted as subglacially formed tunnel valleys.

Two additional types of landform have been described from the northern North Sea sub-basin stratigraphy. These are: elongate lobes (Fig. 12e); and curvilinear ridges and depressions associated with acoustically chaotic sediments (Fig. 12f).

Elongate lobes, with lengths of up to 10 km and widths of up to 2 km, have been reported from palaeo-slope horizons within Units A to D in the northern North Sea (Fig. 12e) (Ottesen et al., 2014; Batchelor et al., 2017). The oldest elongate lobes are identified seaward of Sognefjorden and are around 2 Ma in age. The geometry and dimensions of the elongate lobes suggest that they are glacigenic debris-flows produced by the delivery, and subsequent remobilisation, of subglacial sediment to the shelf break (e.g. Laberg and Vorren, 1995; Dowdeswell et al., 1996; Nygård et al., 2002; Taylor et al., 2002; Laberg and Dowdeswell, 2016). Whereas mega-scale glacial lineations and iceberg ploughmarks have not been identified on early Quaternary palaeo-shelves in the northern North Sea, the interpretation of glacigenic debris-flows on early Quaternary palaeo-slopes (Fig. 12e) provides strong indirect evidence for the extension of the Fennoscandian Ice Sheet (FIS) to the shelf break beyond western Norway, at least intermittently, from close to the onset of the Quaternary (Ottesen et al., 2014, 2016).

Curvilinear ridges and depressions associated with acoustically chaotic sediments (Fig. 12f) have been identified within Unit D in the Norwegian Sea. The acoustically chaotic units are interpreted as mass-transport deposits that were produced during the Stad, Møre and Tampen submarine sediment slides, respectively, which occurred on the North Sea TMF after around 0.5 Ma (Evans et al., 1996; King et al., 1996; Nygård et al., 2005; Hjelstuen and Grinde, 2015; Batchelor et al., 2017). The curvilinear ridges and depressions that are recognised on 3D seismic data (Fig. 12f) are interpreted as rafted sediment blocks that were displaced during the slides.

7. Discussion: morphology and pattern of Quaternary sedimentation in the North Sea Basin

Three sedimentary processes have been dominant within the North Sea Basin during the Quaternary: 1) the delivery of fluvio-deltaic sediments, with a component of glacifluvial sediments, and their basinward transfer via delta-front channels; 2) contourite deposition and the reworking of sediments by contour currents; and 3) the delivery of glacier-derived sediments and their associated basinward transfer as glacigenic debris-flows. Hemipelagic and glacimarine sedimentation most probably also occurred within the basin. Major submarine slides occurred on the North Sea TMF from around 0.5 Ma (King et al., 1996; Nygård et al., 2005; Hjelstuen and Grinde, 2015).

Summary diagrams showing the nature of sedimentation and the importance of each land area as a sediment source, together with the architecture of the North Sea Basin, are presented for four Quaternary time intervals in Figure 13.

7.1 Earliest Quaternary (*c.* 2.6 Ma)

At the beginning of the Quaternary, the North Sea Basin, which has since been infilled by up to 1100 m of Quaternary sediments, extended from the Norwegian Sea to the present-day land area of the Netherlands (Fig. 13a) (Anell et al., 2010; Knox et al., 2010; Lamb et al., 2017). The basin was open to the Norwegian Sea in the north but was separated from the Atlantic Ocean to the south by the Weald-Artois anticlinal bedrock ridge between the UK and France (Gibbard, 1988; Gibbard and Cohen, 2015). The height of clinoforms and the present-day compacted sediment thickness in the northern North Sea (Fig. 8) suggests that the basin had a water depth of at least 600 ms in the central North Sea (540 m). Two largely independent depocentres built up in the North Sea Basin during the earliest Quaternary: a large multi-river deltaic system in the southern and central sub-basin, which was also accumulating during the Pliocene; and a coast-parallel depocentre beyond western Norway in the northern sub-basin.

The delivery of sediments from the Baltic (Eridanos) river system, combined with a smaller component from the Rhine-Meuse river system, was probably the principal mechanism of sediment delivery to the southern and central sub-basin during the earliest Quaternary (Bijlsma, 1981; Gibbard, 1988; Cameron et al., 1992; Overeem et al., 2001; Kuhlmann and Wong, 2008; Westerhoff, 2009; Thøle et al., 2014; Lamb et al., 2017). A significant portion of these sediments may have also been sourced from Scandinavian rivers (Rasmussen et al., 2010; Olivarius et al., 2014). Rivers also drained into the central and southern sub-basin from the UK, with the lower sediment supply from these rivers leading to the formation of smaller deltas along the western basin edge (Fig. 13a) (Cameron et al., 1992). The East Shetland Platform, which was an important source area for sediments during the Late Cenozoic (Eidvin and Rundberg, 2007), continued to provide significant quantities of fluvio-deltaic sediment into the northern North Sea during the early Quaternary. Subsequent to Late Pliocene to Early Pleistocene tilting of the eastern North Sea, significant sediment supply to the basin was probably also from reworked basin-margin areas (Rasmussen et al., 2010).

Several lines of evidence suggest that contour currents were an important mechanism of sediment deposition and reworking in the North Sea Basin during the early Quaternary. In addition to the Shetland Drift, which had been accumulating on the continental slope beyond the Shetland Islands since the late Neogene (Turrell et al., 1999; Knutz and Cartwright, 2003; Hohbein and Cartwright, 2006), contourites developed along the western side of the central basin, as indicated by Unit Z (Figs. 11 and 13a) (Ottesen et al., 2014). Contour-current activity is also suggested by the north-easterly deflection of delta-front channels, which indicate anti-clockwise water circulation within the basin (Knutz, 2010; Lamb et al., 2016). In addition, slope-parallel ridges (Fig. 12a), which are interpreted to have been formed by contour currents, are present throughout the southern and central sub-basin (Fig. 13a) (Kuhlmann and Wong, 2008; Stuart and Huuse, 2012).

The North Sea Basin was a glacially influenced environment discontinuously for most of the Quaternary (Fig. 13a). Evidence for the expansion of the FIS beyond the southern Norway coastline during the early Quaternary includes the presence of elongate lobes, interpreted as glacigenic debris-flow deposits, on palaeo-slope surfaces in the northern North Sea (e.g. Fig. 12e) (Ottesen et al., 2014). Sognefjorden, which is presently the longest and deepest fjord in Norway, was probably a significant source area for glacial sediments during the early Quaternary, as evidenced by the geometry of the Unit A depocentre (Fig. 13a).

The indirect effects of an expanded early Quaternary FIS are recognised across the North Sea Basin. The intensification of Northern Hemisphere glaciation is recorded by an increase in sedimentation rates into the North Sea Basin from around 2.6 Ma (Eidvin et al., 2000; Anell et al., 2012; Kuhlmann and Wong, 2008; Ottesen et al., 2014; Reinardy et al., 2017). Ice-rafted debris is identified in sediment cores in the northern sub-basin from around 2.7 Ma (Eidvin and Rundberg, 2001; Ottesen et al., 2009), whilst iceberg ploughmarks have been interpreted from surfaces dated to around 2 Ma in the southern and central sub-basin (Knutz, 2010; Stuart and Huuse, 2012; Dowdeswell and Ottesen, 2013, 2016; Haavik and Landrø, 2014; Rea et al., 2018). In addition, deltaic sediments in the southern and central sub-basin show variations in seismic amplitude and gamma-ray values that may reflect the glacial-interglacial cycles of the early Quaternary (Kuhlmann and Wong, 2008). High amplitude reflections and low gamma-ray values have been interpreted to result from the deposition of relatively larger grain sizes, such as silt, by bottom currents that operated in warmer conditions. In contrast, finer sediments, such as clay, are interpreted to have been deposited during cooler periods characterised by weaker ocean circulation (Kuhlmann and Wong, 2008).

7.2 Early Quaternary (*c.* 1.6-1.7 Ma)

By the middle of the early Quaternary, around 1.6-1.7 Ma, most of the southern basin and a large part of the northern basin had been infilled (Fig. 13b). This infill comprises sequences 5 to 13 of Kuhlmann and Wong (2008) in the Dutch sector, and Units A and B of Ottesen et al. (2014) in the northern North Sea. Deep sub-basins remained in the central and northern North Sea and provided accommodation space for sediment deposition.

The delivery of fluvio-deltaic sediments from European and Scandinavian river systems continued to be the dominant process within the North Sea Basin, with the delta front advancing progressively to the west and northwest during the early Quaternary (Fig. 13b). A smaller component of fluvial sediment was probably derived from the UK.

Contourites continued to build up to the north of the Shetland Islands. Some contour-current derived sediment may have extended into the partially infilled northern sub-basin subsequent to the deposition of Unit B and prior to the deposition of Unit C (Fig. 13) (Batchelor et al., 2017). The southern and central sub-basin was probably connected by a narrow and shallow corridor to the northern sub-basin during this time, which allowed water from the Norwegian Sea to circulate within the North Sea (Fig. 13b).

The interpretation of glacigenic debris-flows on palaeo-slope surfaces within Unit B provides evidence that the FIS advanced to the palaeo-shelf break in the northern North Sea during several early Quaternary glaciations (Ottesen et al., 2014). The deposition of mainly ice-sheet derived sediments caused the shelf break to prograde in a westerly direction into the northern basin (Fig. 13b). This finding is in broad agreement with the glacial history of the mid-Norwegian margin, which has been interpreted to have experienced several episodes of cross-shelf glaciation during this time (Rise et al., 2005; Ottesen et al., 2009; Montelli et al., 2017). The mapping of mega-scale glacial lineations provides evidence for a grounded ice sheet in the central North Sea Basin during the early Quaternary (Fig. 9g) (Buckley, 2012, 2016; Rose et al., 2016; Rea et al., 2018), although there is uncertainty about the timing of their formation. The oldest age estimate for these mega-scale glacial lineations, which is derived from tying regional seismic mapping to borehole data in the southern North Sea, is around 1.87 Ma (Rea et al., 2018). Although the southern extent of the FIS during the early Quaternary is uncertain, the ice sheet did not advance significantly southwards to block the path of the Baltic (Eridanos) river during this time. Seismic profiles and the record of ice-rafted debris in sediment cores from the northwest British margin suggest that grounded ice was probably restricted to the coastline or inner-shelf of the UK during the early Quaternary (Sejrup et al., 2005; Lee et al., 2012; Thierens et al., 2012).

7.3 Middle Pleistocene Transition (*c.* 1 Ma)

The central and northern North Sea sub-basin was largely infilled by the Middle Pleistocene Transition of around 1.2 to 0.7 Ma (Ruddiman et al., 1989; Head and Gibbard, 2005; Clark et al., 2006). The infilling of the basin, combined with the probable intermittent presence of grounded ice, may have led to the development of an isolated water-body within the central North Sea (Fig. 13c).

Although the delivery of fluvio-deltaic sediment continued to be a significant process in the North Sea during the middle Quaternary, the principal source of this sediment shifted to the Rhine-Meuse and other river systems that drained central and eastern England, including the Thames (Fig. 13c). This has been suggested to be the consequence of intensified erosion by the expanded FIS leading to excavation of the Baltic Basin, which caused the Baltic (Eridanos) river system to lose its connection to the Fennoscandian and Baltic headwaters (Gibbard, 1988; Overeem et al., 2001; Gibbard and Cohen, 2015). Rivers systems in the UK probably had higher sediment budgets and discharge rates in the middle Quaternary compared with during the early Quaternary, leading to them contributing more sediment into the North Sea Basin (Rose et al., 2001; Bridgland et al., 2015; Lee et al., 2018).

The infilling of the North Sea Basin prevented the deposition and reworking of sediments by contour currents in the southern and central North Sea during the Middle Pleistocene Transition. However, contourite lenses, interfingered with glacigenic debris-flows, have been identified within Unit C in the northern North Sea (Fig. 8) (Batchelor et al., 2017). The sequence of alternating contourites and glacigenic debris-flows within Unit C has been interpreted to reflect changes in ocean circulation strength and variations in the nature of sediment delivery to the northern sub-basin during the glacial-interglacial cycles of the early to middle Quaternary (Batchelor et al., 2017).

Multiple lines of evidence suggest that ice-sheet expansion occurred in the North Sea region during the Middle Pleistocene Transition. However, the extent and timing of these events are not well-constrained, as exemplified by the question marks in Figure 13c. The Norwegian Channel Ice Stream of the FIS, which flowed northwards into the Norwegian Sea, has been suggested to have initiated around 1.1 to 0.8 Ma (Sejrup et al., 1995; Ottesen et al., 2014). There is also sedimentary-stratigraphic evidence that the FIS extended into northern Denmark between around 1.2 and 1 Ma (Houmark-Nielsen, 2004). In the Netherlands, the erratic gravels and boulders of the Hattem Beds have been suggested to have been transported, in part at least, by an expanded FIS of assumed Menapian (*c.* 1.2 Ma) age (Zagwijn, 1985). In addition, the Crag Group units in East Anglia contain clusters of erratics that are derived from Norway and Scotland and are interpreted to have melted-out from grounded icebergs in coastal areas during at least one glaciation between *c.* 1.1 and 0.6 Ma (Larkin et al., 2011).

The presence of northeast-southwest-trending lineations, interpreted as mega-scale glacial lineations, on 3D seismic data from the Norwegian sector of the northern North Sea suggests that an ice stream of the FIS extended from southwest Norway into the central North Sea, prior to the initiation of the Norwegian Channel Ice Stream (Reinardy et al., 2017). Our identification of northeast-southwest orientated mega-scale glacial lineations on a prominent glacial erosion surface (top of Clinoform Unit 3) at the eastern side of the central basin (Figs. 9g and 12c) strongly supports this interpretation. Some of the mega-scale glacial lineations reported from the Crenulate Marker in the British sector are located immediately to the southwest of and have similar orientation to the mega-scale glacial lineations that extend from the Norwegian mainland (Figs. 9g and 12c). Although it is possible that an ice stream of the BIIS extended into the central North Sea during this time, and became virtually confluent with an ice stream of the FIS, the mega-scale glacial lineations on the Crenulate Marker may alternatively have been formed by an ice stream that extended from the Norwegian mainland (Fig. 13c). The latter interpretation does not require ice streams of the FIS and BIIS to meet in the central North Sea during this time.

7.4 Middle and late Quaternary (*c.* 0.5 – 0 Ma)

By around 0.5 Ma, which corresponds with the Elsterian (Anglican) Stage glaciation of the middle Quaternary (430-450 ka), the North Sea Basin was largely infilled (Fig. 13d). The FIS and BIIS were confluent in the North Sea and attained a maximum southerly position close to the present-day coastlines of the Netherlands and East Anglia, UK (Ehlers, 1990, Ehlers et al., 2011; Clark et al., 2004; Gibbard and Clark, 2011; Lang et al., 2018).

The Rhine-Meuse and palaeo-Thames river systems continued to transfer water and sediments towards the North Sea. The flow of these rivers may have been deflected by the presence of the Eurasian Ice Sheet, causing water to pool and form a large lake beyond the ice margin (Fig. 13d) (Gibbard, 1988, 1995; Gupta et al., 2007; Gibbard and Cohen, 2015). The morphology of the North Sea Basin changed dramatically during the middle Quaternary when overflow of the lake resulted in the erosion and breaching of the Weald-Artois bedrock ridge that connected the UK to mainland Europe (Fig. 13d) (Smith, 1985; Gibbard, 1988, 1995; Gibbard and Cohen, 2015). Although the Weald-Artois ridge was initially breached during the Elsterian (Anglican) Stage, it was not until the late Saalian Stage glaciation of MIS 6 (around 0.16 Ma) that this barrier was entirely removed, linking the North Sea to the Atlantic Ocean via the English Channel during periods of high global sea-level (Busschers et al., 2008; Mathys, 2009; Cohen et al., 2014; Gibbard and Cohen, 2015).

In contrast to the early Quaternary, contour-current deposition was not a significant process in the North Sea Basin during the middle Quaternary. The Shetland Drift ceased accumulating; its upper surface is defined by a glacial unconformity that has been interpreted to mark the onset of shelf-break glaciation on the Hebrides margin at around 0.44 Ma (Stoker et al., 1994). The North Sea Fan was characterised by net contour-current erosion, with isolated contourite deposits probably accumulating only within slide scars (Bryn et al., 2005; Batchelor et al., 2017).

The southern, central and northern North Sea was affected greatly by the expanded Eurasian Ice Sheet during the middle and late Quaternary. The formation of a prominent glacigenic unconformity at around 0.5 Ma (Moreau et al., 2012) provides the first direct evidence for an ice sheet in the southern North Sea. The Eurasian Ice Sheet also extended over most of the North Sea during the penultimate glaciation of MIS 6 and during the Last Glacial Maximum (Fig. 13d) (Ehlers et al., 2011). The relatively flat-lying middle to late Quaternary sediments of the southern and central North Sea have complex internal geometry on seismic profiles (e.g. Figs. 5-7), which includes incision by up to seven generations of tunnel valleys (Praeg, 2003; Lonergan et al., 2006; Stewart and Lonergan, 2011; Stewart, 2016). These tunnel valleys form complex anatomising networks of filled valleys up to 100 km long, 5 km wide, and 500 m deep (Ó Cofaigh, 1996; Praeg, 2003; Stewart et al., 2013). Major glaciotectonic thrusting and folding associated with advances of the Eurasian Ice Sheet during the middle and late Quaternary have also been reported from the central North Sea (Cotterill et al., 2017; Vaughan-Hirsch and Phillips, 2017).

The Norwegian Channel Ice Stream, which was initiated between about 1.1 and 0.8 Ma, became a prominent feature of the Eurasian Ice Sheet during the middle and late Quaternary (Fig. 13d). The orientation of elongate lineations on palaeo-shelf surfaces, interpreted as mega-scale glacial lineations, suggests that the Norwegian Channel Ice Stream initially flowed across Måløy Plateau, which is presently a shallow bank, and subsequently migrated around 60 km to the west during the middle to late Quaternary (Nygård et al., 2004; Rise et al., 2004, 2016; Batchelor et al., 2017). The Norwegian Channel Ice Stream delivered high rates of ice-sheet derived sediments to the North Sea TMF during these full-glacial periods (Fig. 13d), with up to 90% of the fan volume being deposited during the last 0.5 Ma (Hjelstuen et al., 2012). The onset of major mass-movement events on the North Sea Fan coincides with ice-sheet expansion across the shelf to the north of the Shetland Islands at around 0.5 Ma (Stoker et al., 1994; Sejrup et al., 2005). This suggests that the initiation of sediment slides on the TMF may have been encouraged by increased rates of sediment delivery to the shelf break (King et al., 1996, 1998).

8. Conclusions

We have used an extensive database of 2D and 3D seismic data to correlate major Quaternary seismo-stratigraphic surfaces and units across the North Sea, from 52°N-62°N (Fig. 1). We present new maps of Quaternary basin morphology and sediment thickness that reveal the infill pattern of the entire North Sea Basin and enable small-scale features to be placed within a basin-wide context (Figs. 3, 4, 9 and 10).

- We reinterpret part of the base-Quaternary surface in the central North Sea basin. The base-Quaternary surface is shown to be dominated by two deep depressions (Fig. 3a). The southern and central sub-basin is elongate in a NNW-SSE direction and reaches a maximum depth of *c.*1100 m along its central axis. The northern sub-basin extends from the northern North Sea to the Norwegian Sea. By around 1.6-1.7 Ma, most of the southern North Sea Basin and a large part of the northern sub-basin had been infilled, with a deep depression remaining in the central North Sea (Fig. 13b). This central depression was infilled gradually during the second half of the early Quaternary (Fig. 9e to i).

- Two largely independent depocentres developed in the North Sea Basin during the Quaternary: one in the southern and central sub-basin, and the other in the northern sub-basin (Figs. 3 and 4). The total volume of Quaternary sediments in the North Sea, within the 500 m contour of the base-Quaternary surface, is 109,000 km^3 (Table 1). Of these, 88,000 km^3 (81%) are in the southern and central sub-basin, and 92,000 km^3 (84%) are below the URU and URU-equivalent surface.
- The dominant sedimentary processes in the North Sea Basin during the Quaternary are: 1) the delivery and downslope transfer of fluvio-deltaic sediments; 2) the delivery and downslope transfer of glacier-derived sediments; and 3) the deposition and reworking of sediments by contour currents (Fig. 13).
- The southern and central North Sea sub-basin was infilled mainly by fluvio-deltaic sediments derived from European and Scandinavian rivers during the early Quaternary (Fig. 13a and b). Significant quantities of fluvio-deltaic sediment were also delivered to the northern sub-basin from the East Shetland Platform during this time. As a consequence of intensified ice-sheet erosion, the principal source of fluvio-deltaic sediment to the North Sea Basin shifted from the Baltic (Eridanos) river system in the east to the Rhine-Meuse and Thames river systems in the south around the Middle Pleistocene Transition (Fig. 13c).
- A coast-parallel depocentre containing ice-sheet derived sediments provides evidence that the FIS extended intermittently to the palaeo-shelf break in the northern North Sea during the earliest Quaternary (Fig. 13a). The presence of elongate lineations, interpreted as mega-scale glacial lineations, on 3D seismic data (Fig. 12c) indicates that the FIS expanded into the central North Sea during the early Quaternary prior to the initiation of the Norwegian Channel Ice Stream (Figs. 9g and 12c).
- The presence of contourite drifts (Fig. 13a) and contour-current ridges (Fig. 12a) suggests that contour currents were an important mechanism of sediment deposition and reworking in the North Sea Basin during the early Quaternary. Water circulation in the basin was probably in an anti-clockwise direction (Fig. 13a and b). The infilling of the North Sea Basin precluded contour-current activity during the mid- and late-Quaternary.

Acknowledgements

We thank Mærsk Oil and Gas Ltd., PGS, Searcher Seismic, Statoil ASA and TGS for access to seismic data. Olex AS is thanked for access to regional bathymetric data and Schlumberger for access to the Petrel software. Shyam Chand helped with seismic data processing. Tove Nielsen is thanked for access to a grid of the base Quaternary surface on the Danish shelf. We thank Leif Rise, Tor Eidvin and Phil Gibbard for providing comments on draft versions of the manuscript. We also thank Jonathan Lee, Erik Rasmussen and an anonymous reviewer for their helpful reviews of this paper.

References

Anell, I., Thybo, H., Stratford, W., 2010. Relating Cenozoic North Sea sediments to topography in southern Norway: The interplay between tectonics and climate. Earth Plan. Sci. Lett. 300, 19-32.

Anell, I., Thybo, H., Rasmussen, E., 2012. A synthesis of Cenozoic sedimentation in the North Sea. Basin Res. 24, 154-179.

Arfai, J., Franke, D., Lutz, R., Reinhardt, L., Kley, J., Gaedicke, C., 2018. Rapid Quaternary subsidence in the northwestern German North Sea. Scientific Reports 8, 11524.

Batchelor, C.L., Ottesen, D., Dowdeswell, J.A., 2017. Quaternary evolution of the northern North Sea margin through glacigenic debris-flow and contourite deposition. J. Quat. Sci. 32(3), 416-426. Doi: 10.1002/jqs.2934.

Bijlsma, S., 1981. Fluvial sedimentation from the Fennoscandian area into the Northwest European Basin during the Late Cenozoic. Geol. Mijnb. 8, 337-345.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., Mathers, H.M., 2008. The northern sector of the last British Ice Sheet: Maximum extent and demise. Earth-Sci. Rev. 88, 207-226.

Bridgland, D.R., Howard, A.J., White, M.J., White, T.S., Westaway, R., 2015. New insight into the Quaternary evolution of the River Trent, UK. Proc. Geol. Ass. 126, 466-479.

Bryn, P., Berg, K., Stoker, M., Haflidason, H., Solheim, A., 2005. Contourites and their relevance for mass waisting along the Mid-Norwegian Margin. Mar. Pet. Geol. 22, 85-96.

Buckley, F.A., 2012. An Early Pleistocene grounded ice sheet in the Central North Sea. In: Huuse, M., Redfern, J., Le Heron, D.P., Dixon, R.J., Moscariello, A., Craig, J. (Eds.), Glaciogenic Reservoirs and Hydrocarbon Systems. Geol. Soc. London, Spec. Publ. 368, 185-209.

Buckley, F.A., 2016. A glaciogenic sequence from the Early Pleistocene of the Central North Sea. J. Quat. Sci. 32(2), 145-168, DOI: 10.1002/jqs.2867.

Busschers, F.S., van Balen, R.T., Cohen, K.M., Kasse, C., Weerts, H.J.T., Wallinga, J., Bunnik, F.P.M., 2008. Response of the Rhine–Meuse fluvial system to Saalian ice-sheet dynamics. Boreas 37, 377-398.

Cameron, T.D.J., Stoker, M.S., Long, D., 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. J. Geol. Soc. 144, 43-58.

Cameron, T.D.J., Crossby, A., Balson, P.S. et al., 1992. The geology of the southern North Sea. United Kingdom offshore regional report 7. Brit. Geol. Surv., London.

Cameron, T.D.J., Bulat, J., Mesdag, C., 1993. High-resolution seismic profile through a Late Cenozoic delta complex in the southern North Sea. Mar. Pet. Geol. 10, 591-599.

Caston, V.N.D., 1977. A new Isopachyte Map of the Quaternary of the North Sea. Inst. Geol. Sci. Rep. 10/11, pp. 3-10.

Clark, C.D., Gibbard, P.L., Rose, J., 2004. Pleistocene glacial limits in England, Scotland and Wales, In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations - Extent and Chronology Part 1: Europe. Elsevier, Amsterdam, pp. 47-82.

Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., Mix, A.C., Pisias, M.G., Roy, M., 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. Quat. Sci. Rev. 25, 3150-3184.

Cohen, K.M., Gibbard, P.L., Weerts, H.J.T., 2014. North Sea palaeogeographical reconstructions for the last 1 Ma. Neth. J. Geosci. 93, 7-29.

Cotterill, C.J., Phillips, E., James, L., Forsberg, C.F., Tjelta, T.I., Carter, G., Dove, D., 2017. The evolution of the Dogger Bank, North Sea: a complex history of terrestrial, glacial and marine environmental change. Quat. Sci. Rev. 171, 136-153.

Dahlgren, K.I., Vorren, T.O., Laberg, J.S., 2002. Late Quaternary glacial development of the mid-Norwegian margin – 65-68°N. Mar. Pet. Geol. 19, 1089-1113.

De Schepper, S., Mangerud, G., 2017. Age and palaeoenvironment of the Utsira Formation in the northern North Sea based on marine palynology. Norw. J. Geol. 97, 305-325.

Dowdeswell, J.A., Ottesen, D., 2013. Buried iceberg ploughmarks in the early Quaternary sediments of the central North Sea: a two-million-year record of glacial influence from 3D seismic data. Mar. Geol. 344, 1-9.

Dowdeswell, J.A., Ottesen, D., 2016. Three-dimensional seismic imagery of deeply buried iceberg ploughmarks in North Sea sediments. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.), Atlas of Submarine

Glacial Landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem. 46, 291-292.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., Siegert, M.J., 1996. Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: Long-range side-scan sonar evidence. Geophys. Res. Lett. 23, 3535-3538.

Dowdeswell, J.A., Ottesen, D., Rise, L., Craig, J., 2007. Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. Geology 35, 359-362.

Ehlers, J., 1990. Reconstructing the dynamics of the north-west European Pleistocene ice sheets. Quat. Sci. Rev. 9, 71-83.

Ehlers, J., Gibbard, P.L., Hughes, P.D., 2011. Quaternary Glaciations - Extent and Chronology. Elsevier.

Eidvin, T., Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. Norw. J. Geol. 81, 119-160.

Eidvin, T., Rundberg, Y., 2007. Post-Eocene strata of the southern Viking Graben, northern North Sea; integrated biostratigraphic, Strontium isotope and lithostratigraphic study. Norw. J. Geol. 87, 391-450.

Eidvin, T., Riis, F., Rundberg, Y., 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Norw. J. Geol. 79, 97-128.

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H., Grogan, P., 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic. Mar. Pet. Geol. 17, 579-600.

Eidvin, T., Riis, F., Rasmussen, E.S., Rundberg, Y., 2013. Investigation of Oligocene to Lower Pliocene deposits in the Nordic offshore area and onshore Denmark. Norw. Pet. Dir. Bull. 10, 1-62.

Evans, D., King, E.L., Kenyon, N.H., Brett, C., Wallis, D., 1996. Evidence for long-term instability in the Storegga Slide region off western Norway. Mar. Geol. 30, 281-292.

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S., Bjerke, M.D., 2002. Tectonic impact on Sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. In: Dore, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P., White, N. (Eds.), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Spec. Publ., Geol. Soc. London 196, 235-270.

Faugeres. J.C., Stow, D.A.V., Imbert, P., Viana, A.R., 1999. Seismic features diagnostic of contourite drifts. Mar. Geol. 162, 1-38.

Funnell, B.M., 1996. Plio-Pleistocene palaeogeography of the southern North Sea Basin (3.75-0.60 Ma). Quat. Sci. Rev. 15, 391-405.

Fyfe, J.A., Gregersen, U. et al., 2003. Oligocene to Holocene. In: Evans, D., Graham, C., Armour, A., Bathurst, P. (Eds.), The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geol. Soc., London, 279-287.

Gabrielsen, R.H., Faleide, J.I., Pascal, C., Braathen, A., Nystuen, J.P., Etzelmuller, B., O'Donnell, S., 2010. Latest Caledonian to Present tectonomorphological development of southern Norway. Mar. Pet. Geol. 27, 709-723.

Galloway, W.E., 2002. Paleogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea Basin. J. Sed. Res. 72, 477-490.

Galloway, W.E., Garber, J.L., Xijin, L., Sloan, B.J., 1993. Sequence stratigraphy and depositional framework of the Cenozoic fill, Central and Northern North Sea Basin. In: Parker, J.R. (Ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geol. Soc. London, London, pp. 33-43.

Gatliff, R.W., Richards, P.C., Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., Long, D., Cameron, T.D.J., Evans, D., Stevenson, A.G., Bulat, J., Ritchie, J.D., 1994. The geology of the central North Sea. UK Offshore regional Report, Brit. Geol. Surv.

Gibbard, P.L., 1988. The history of the great northwest European rivers during the past three million years. Phil. Trans. Royal Soc.. London, Series B, 318, 559-602.

Gibbard, P.L., 1995. The formation of the Strait of Dover. Geol. Soc., London, Spec. Publ. 96, 15-26.

Gibbard, P.L., Clark, C.D., 2011. Chapter 7 - Pleistocene Glaciation Limits in Great Britain. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations - Extent and Chronology - A Closer Look. Developments in Quaternary Science 15.

Gibbard, P.L., Cohen, K.M., 2015. Quaternary evolution of the North Sea and the English Channel. Proceedings of the OUGS 1, 63-74.

Gibbard, P.L., Lewin, J., 2016. Filling the North Sea Basin: Cenozoic sediment sources and river styles. Geol. Belgica 19, 201-217.

Goledowski, B., Nielsen, S.B., Clausen, O.R., 2012. Patterns of Cenozoic sediment flux from western Scandinavia. Basin Res. 24, 377-400.

Graham, A.G.C., Lonergan, L., Stoker, M., 2010. Depositional environments and chronology of Late Weichselian glaciations and deglaciation in the central North Sea. Boreas 39, 471-491.

Graham, A., Stoker, M.S., Lonergan, L., Bradwell, T., Stewart, M., 2011. The Pleistocene glaciations of the North Sea Basin. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations: Extent and Chronology: a Closer Look. Developments in Quaternary Science 15. Elsevier, pp. 261-278.

Gregersen, U., Johannessen, P.N., 2007. Distribution of the Neogene Utsira Sand and the succeeding deposits in the Viking Graben area, North Sea. Mar. Pet. Geol. 24, 591-606.

Gupta, S., Collier, J.S., Palmer-Felgate, A., Potter, G., 2007. Catastrophic flooding origin of shelf valley systems in the English Channel. Nature 448, 342-345.

Haavik, K.E., Landrø, M., 2014. Iceberg ploughmarks illuminated by shallow gas in the central North Sea. Quat. Sci. Rev. 103, 34-50.

Head, M.J., Riding, J.B., Eidvin, T., Chadwick, R., 2004. Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea. Mar. Pet. Geol. 21, 277-297.

Head, M.J., Gibbard, P.L., 2005. Early-Middle Pleistocene transitions: an overview and recommendation for the defining boundary. Geol. Soc., London, Spec. Publ. 247, pp. 1-18.

Hjelstuen, B.O., Grinde, S., 2015. 3D seismic investigation of Pleistocene Mass Transport Deposits and Glacigenic Debris Flows on the North Sea Fan, NE Atlantic Margin. In: Lamarche, G. et al. (Eds.), Submarine Mass Movements and Their Consequences, Advances in Nat. and Technol. Hazard Res., pp. 265-272.

Hjelstuen, B.O., Nygård, A., Sejrup, H.P., Haflidason, H., 2012. Quaternary denudation of southern Fennoscandia – evidence from the marine realm. Boreas 41, 379-390.

Hohbein, M., Cartwright, J., 2006. 3D seismic analysis of the West Shetland Drift System: Implications for Late Neogene palaeoceanography of the NE Atlantic. Mar. Geol. 230, 1-20.

Houmark-Nielsen, M., 2004. The Pleistocene of Denmark, a review of stratigraphy and glaciation history. Quaternary Glaciations - Extent and chronology. Part 1. Europe. 2 edition. Elsevier, Amsterdam, pp. 35-46.

Huuse, M., Kristensen, T.B., 2016. Pleistocene tunnel valleys in the North Sea Basin. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.), Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem. 46, 207-208.

Huuse, M., Lykke-Andersen, H., 2000. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quat. Sci. Rev. 19, 1233-1253.

Huuse, M., Lykke-Andersen, H., Michelsen, O., 2001. Cenozoic evolution of the eastern Danish North Sea. Mar. Geol. 177, 232-269.

Johnson, H., Richards, P.C., Long, D., Graham, C.C., 1993. United Kingdom offshore regional report: the geology of the northern North Sea. London: HMSO for the Brit. Geol. Surv.

Jordt, H., Faleide, J.I., Bjørlykke, K., Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea. Tectonic development, sediment distribution and provenance area. Mar. Pet. Geol. 12, 845-879.

King, C., 1983. Cainozoic micropaleontological biostratigraphy of the North Sea – Rept. Init. Geol. Sciences, No. 82/7, 40pp.

King, C., 1989. Cenozoic of the North Sea. In: Jenkins, D.G., Murray, J.W. (Eds.), Stratigraphical Atlas of Fossil Foraminifera, Ellis Horwood Ltd., pp. 418–489.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhøi, A., Aarseth, I., 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially fed gravity flow aprons, hemipelagic sediments, and large submarine slides. Mar. Geol. 130, 293-315.

King, E.L., Haflidason, H., Sejrup, H.P., Løvlie, R., 1998. Glacigenic debris flows on the North Sea Trough Mouth Fan during ice stream maxima. Mar. Geol. 152, 217-246.

Knox, R.W.O.B., Bosch, J.H.A., Rasmussen, E.S., Heilmann-Clausen, C., Hiss, M., De Lugt, I.R., Kasinksi, J., King, C., Køthe, A., Slodkowska, B., Standke, G., Vanderberghe, N., 2010. Cenozoic. In: Doornenbal, J.C., Stevenson, A.G. (Eds.), Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publication b.v. (Houten), pp. 211-223.

Knutz, P.C., 2010. Channel structures formed by contour currents and fluid expulsion: significance for Late Neogene development of the central North Sea basin. In: Vining, B.A., Pickering, S.C. (Eds.), Petroleum Geology: from Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference. Geol. Soc., London, pp. 77–94, doi:10.1144/0070077.

Knutz, P., Cartwright, J.A., 2003. Seismic stratigraphy of the West Shetland Drift: implications for North Atlantic circulation. Palaeoceanography 18. DOI: 10.1029/2002PA000786.

Kooi, H., Hettema, M., Cloetingh, S., 1991. Lithosphere dynamics and the rapid Pliocene-Quaternary subsidence phase in the southern North Sea Basin. Tectonophysics 192, 245-259.

Kuhlmann, G., Wong, T.E., 2008. Pliocene paleoenvironmental evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. Mar. Pet. Geol. 25, 173-189.

Kuhlmann, G., Langreis, C., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulemkamp, J., Wong, T., 2006. Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations. Palaeogeography, Palaeoclimatology, Palaeoecology 239, 426-455.

Laberg, J.S., Vorren, T.O., 1995. Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Mar. Geol. 127, 45-72.

Laberg, J.S., Dowdeswell., J.A., 2016. Glacigenic debris-flows on the Bear Island Trough-Mouth Fan, Barents Sea margin. In: Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K., Hogan, K. A., (Eds.), Atlas of Submarine Glacial landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem., 46, pp. 367-368.

Lamb, R.M., Huuse, M., Stewart, M., 2016. Early Quaternary sedimentary processes and palaeoenvironments in the central North Sea. J. Quat. Sci.. DOI: 10.1002/jqs.2894.

Lamb, R.M., Harding, R., Huuse, M., Stewart, M., Brocklehurst, S.H., 2017. The early Quaternary North Sea Basin. J. Geol. Soc.. Doi 10.1144/jgs2017-057.

Lang, J., Lauer, T., Winsemann, J., 2018. New age constraints for the Saalian glaciations in northern central Europe: Implications for the extent of ice sheets and related proglacial lake systems. Quat. Sci. Rev. 180, 240-259.

Larkin, N.R., Lee, J.R., Connell, E.R., 2011. Possible ice-rafted erratics in late Early to early Middle Pleistocene shallow marine and coastal deposits in northeast Norfolk, UK. Proc. Geol. Ass. 122, 445-454.

Lee, J.R., Busschers, F.S., Sejrup, H.P., 2012. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. Quat. Sci. Rev. 44, 213-228.

Lee, J.R., Candy, I., Haslam, R., 2018. The Neogene and Quaternary of England: landscape evolution, tectonics, climate change and their expression in the geological record. Proc. Geol. Ass. 129, 452-481.

Lonergan, L., Maidment, S.C.R., Collier, J.S., 2006. Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. J. Quat. Sci. 21, 891-903.

Løseth, H., Rodrigues, N., Cobbold, P.R., 2012. World's largest extrusive body of sand? Geology 40, 467-470.

Løseth, H., Raulline, B., Nygård, A., 2013. Late Cenozoic geological evolution of the northern North Sea: development of a Miocene unconformity reshaped by large-scale Pleistocene sand intrusion. J. Geol. Soc. London 170, 133-145.

Lutz, R., Kalka, S., Gaedicke, C., Reinhardt, L., Winsemann, J., 2009. Pleistocene tunnel valleys in the German North Sea: spatial distribution and morphology. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 160, 225-235.

Mathys, M., 2009. The Quaternary geological evolution of the Belgian Continental Shelf, southern North Sea. PhD thesis, University of Ghent.

Michelsen, O., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G., Thomsen, E., 1995. Occurence of major sequence stratigraphic boundaries in relation to basin development in Cenozoic deposits of the southeastern North Sea. In: Steel, R.J., Felt, V.L., Johannesen, E.P., Mathieu, C. (Eds.), Sequence stratigraphy: Advances and Applications for Exploration and Producing in North West Europe. Norw. Pet. Soc., NPF Spec. Publ. 5, 415-427.

Montelli, A., Dowdeswell, J.A., Ottesen, D., Johansen, S.E., 2017. Ice-sheet dynamics through the Quaternary on the mid-Norwegian continental margin inferred from 3D seismic data. Mar. Pet. Geol. 80, 228-242.

Moreau, J., Huuse, M., Janszen, A., van der Vegt, P., Gibbard, P.L., Moscariello, A., 2012. The glaciogenic unconformity of the southern North Sea. In: Huuse, M., Redfern J., Le Heron, D., Dixon, R.J., Moscariello, A., Craig, J., (Eds.), Glaciogenic Reservoirs and Hydrocarbon Systems. Geol. Soc. London, Spec. Publ. 368, 99-110.

Nielsen, T., Mathiesen, A., Bryde-Auken, M., 2007. Base-Quaternary in the Danish parts of the North Sea and Skagerrak. Geol. Surv. Denm. Greenl. Bull. 15, 37-40.

Noorbergen, L.J., Lourens, L.J., Munsterman, D.K., Vereussel, R.M.C.H., 2015. Stable isotope stratigraphy of the early Quaternary of borehole Noordwijk, southern North Sea. Quat. Int. 386, 148-157.

Nygård, A., Sejrup, H.P., Haflidason, H., King, E.L., 2002. Geometry and genesis of glacigenic debris flows on the North Sea Fan: TOBI imagery and deep tow boomer evidence. Mar. Geol. 188, 15-33.

Nygård, A., Sejrup, H.P., Haflidason, H., Cecchi, M., Ottesen, D., 2004. Deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 ^{14}C ka BP. Boreas 33, 1-17.

Nygård, A., Sejrup, H.P., Haflidason, H., Bryn, P., 2005. The glacial North Sea Fan, southern Norwegian Margin: architecture and evolution from the continental slope to the deep-sea basin. Mar. Pet. Geol. 22, 71-84.

Nøttvedt, A., Gabrielsen, R., Steel, R.J., 1995. Tectonostratigraphy and sedimentary architecture of rift basins, with reference to the northern North Sea. Mar. Pet. Geol. 12, 881-901.

O'Cofaigh, C., 1996. Tunnel valley genesis. Progress in Physical Geography 20, 1-19.

Olivarius, M., Rasmussen, E.S., Siersma, V., Knudsen, C., Kokfelt, T.F., Keulen, N., 2014. Provenance signal variations caused by facies and tectonics: Zircon age and heavy mineral evidence from Miocene sand in the north-eastern North Sea Basin. Mar. Pet. Geol. 49, 1-14.

Ottesen, D., Rise, L., Andersen, E.S., Bugge, T., Eidvin, T., 2009. Geological evolution of the Norwegian continental shelf between 61°N and 68°N during the last 3 million years. Norw. J. Geol. 89, 251-265.

Ottesen, D., Dowdeswell, J.A., Bugge, T., 2014. Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56°-62°N). Mar. Pet. Geol. 56, 123-146.

Ottesen, D., Dowdeswell, J.A., Bugge, T., 2016. Deeply buried glacigenic debris-flows imaged in 3D seismic data from early Quaternary sediments of the northern North Sea. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.) Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem. 46, 369-370.

Overeem, I., Weltje, G.J., Bishop-Kay, C., Kroonenberg, S.B., 2001. The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? Basin Res. 13, 293-312.

Praeg, D., 1996. Morphology, stratigraphy and genesis of buried mid-Pleistocene tunnel-valleys in the southern North Sea basin. PhD thesis, University of Edinburgh.

Praeg, D., 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin - high resolution from low frequencies. J. Applied Geophys. 53, 273-298.

Rasmussen, E.S., Vejbaek, O.V., Bidstrup, T., Piasecki, S., Dybkjaer, K., 2005. Late Cenozoic depositional history of the Danish North Sea Basin: implications for the petroleum systems in the Kraka, Halfdan, Siri and Nini fields. In: Doré, A.G., Vining, B.A., (Eds.), Petroleum Geology: North-West Europe and Global Perspectives, pp. 1347-1358.

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2010. Lithostratigraphy of the Upper Oligocene - Miocene succession of Denmark. Geol. Surv. Den. Greenl. Bull. 22, 1-92.

Rea, B.R., Newton, A.M.W., Lamb, R.M., Harding, R., Bigg, G.R., Rose, P., Spagnolo, M., Huuse, M., Carter, J.M.L., Archer, S., Buckley, F., Halliyeva, M., Huuse, J., Cornwell, D.G., Brocklehurst, S.H., Howell, J.A., 2018. Extensive marine-terminating ice sheets in Europe from 2.5 million years ago. Science Advances, 4, eaar8327.

Reinardy, B.T.I., Sejrup, H.P., Hjelstuen, B.O., King, E., Augedal, H., 2017. A Quaternary aminostratigraphy constraining chronology of depositional environments in the North Sea Basin. Mar. Geol. 402, 139-152.

Riis, F., 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. Glob. Planet. Change 12, 331-357.

Rijsdijk, K.F., Passchier, S., Weerts, H.J.T. et al., 2005. Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach. Netherlands J. Geosci. 84, 129-146.

Rise, L., Olesen, O., Rokoengen, K., Ottesen, D., Riis, F., 2004. Mid-Pleistocene ice drainage pattern in the Norwegian Channel imaged by 3D seismics. Quat. Sci. Rev. 23, 2323-2335.

Rise, L., Ottesen, D., Berg, K., Lundin, E., 2005. Large-scale development of the mid-Norwegian margin during the last 3 million years. Mar. Pet. Geol. 22, 33-44.

Rise, L., Ottesen, D., Olesen, O., Dowdeswell, J.A., 2016. Buried mega-scale glacial lineations in the Norwegian Channel from 3D seismic imagery. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.), Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem. 46, 179-180.

Rose, J., Moorlock, B.S.P, Hamblin, R.J.O., 2001. Pre-Anglian fluvial and coastal deposits in Eastern England: lithostratigraphy and palaeoenvironments. Quat. Int. 79, 5-22.

Rose, P., Byerley, G., Vaughan, O., Cater, J., Rea, B.R., 2016. Aviat: a Lower Pleistocene shallow gas hazard developed as a fuel gas supply for the Forties Field. In: Bowman, M., Levell, B. (Eds.), Petroleum Geology of NW Europe: 50 Years of Learning. Proceedings of the 8th Petroleum Geology Conference. Geol. Soc. London.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., Backman, J., 1989. Pleistocene evolution: Northern hemisphere ice sheets and North Atlantic Ocean. Paleoceanography and Paleoclimatology 4, 353-412.

Rundberg, Y., Eidvin, T., 2005. Controls on depositional history and architecture of the Oligocene-Miocene succession, northern North Sea. In: Wandås, B., Nystuen, J.P., Eide, E.A., Gradstein, F.M., (Eds.), Onshore-offshore relationships on the North Atlantic margin. Norsk Petroleumsforening (NPF), Spec. Publ. 12, 207-239.

Sejrup, H.P., Aarseth, I., Haflidason, H., Løvlie, R., Bratten, Å., Tjøstheim, G., Forsberg, C.F., Ellingsen, K.L., 1995. Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. Norw. J. Geol. 75, 65-87.

Sejrup, H.P., Larsen, E., Landvik, J. King, E.L., Haflidason, H., Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region: Quat. Sci. Rev. 19, 667-685.

Sejrup, H.P., Larsen, E., Haflidason, H., Berstad, I.M., Hjelstuen, B.O., Jonsdottir, H., King, E.L., Landvik, J.Y., Longva. O., Nygard, A., Ottesen, D., Raunholm, S., Rise, L., Stalsberg, K., 2003. Configuration, history and impact of the Norwegian Channel Ice Stream: Boreas 32, 18-36.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. Mar. Pet. Geol. 22, 1111-1129.

Smith, A.J., 1985. Catastrophic origin for the palaeovalley system of the eastern English Channel. Mar. Geol. 64, 65-75.

Stewart, I.J., 1987. A revised stratigraphic interpretation of the early Paleogene of the Central North Sea. In: Brooks, J., Glennie, K. (Eds.), Petroleum Geology of the North West Europe. Graham and Trotman, London. Pp. 557-576.

Stewart, M.A., 2016. Assemblage of buried and seabed tunnel valleys in the central North Sea: From morphology to ice-sheet dynamics. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.), Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geol. Soc., London, Mem. 46, 317-320.

Stewart, M.A., Lonergan, L., 2011. Seven glacial cycles in the middle-late Pleistocene of northwest Europe; geomorphic evidence from buried tunnel valleys. Geology 39, 283-286.

Stewart, M.A., Lonergan, L., Hampson, G., 2013. 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. Quat. Sci. Rev. 72, 1-17.

Stoker, M.S., Skinner, A.C., Fyfe, J.A., Long, D., 1983. Palaeomagnetic evidence for early Pleistocene in the central and northern North Sea. Nature 304, 332-334.

Stoker, M.S., Leslie, A.B., Scott, W.D. and 6 others, 1994. A record of Late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Slope, NE Atlantic Ocean. J. Geol. Soc. London 151, 235-249.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., Shannon, P., 2005. Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. Mar. Pet. Geol. 22, 977-1005.

Stoker, M.A., Balson, P.S., Long, D., Tappin, D.R., 2011. An overview of the lithostratgraphical framework for the Quaternary deposits on the United Kingdom continental shelf. Brit. Geol. Surv. Res. Rep., RR/11/03, 48 pp.

Stokes, C., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. Ann. Glac. 28, 67-74.

Stuart, J.Y., Huuse, M., 2012. 3D seismic geomorphology of a large Plio-Pleistocene delta – bright spots and contourites in the Southern North Sea. Mar. Pet. Geol. 38, 85-93.

Stuevold, L.M., Eldholm, O., 1996. Cenozoic uplift of Fennoscandia inferred from a study of the mid-Norwegian margin. Global Plan. Change 12, 359-386.

Sørensen, J.C., Michelsen, O., 1995. Upper Cenozoic sequences in the southeastern North Sea Basin. Bull. Geol. Soc. Denm. 42, 74-95.

Sørensen, J.C., Gregersen, U., Breiner, M., Michelsen, O., 1997. High-frequency sequence stratigraphy of Upper Cenozoic deposits in the central and southeastern North Sea areas. Mar. Pet. Geol. 14, 99-123.

Taylor, J., Dowdeswell, J.A., Siegert, M.J., 2002. Late Weichselian depositional processes, fluxes, and sediment volumes on the margins of the Norwegian Sea (62-75°N). Mar. Geol. 188, 61-77.

Thierens, M., Pirlet, H., Colin, C., Latruwe, K., Vanhaecke, F., Lee, J.R., Stuut, J.B., Titschack, J., Huvenne, V.A.I., Dorschel, B., Wheeler, A.J., Henriet, J.P., 2012. Ice-rafting from the British–Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. Quat. Sci. Rev. 44, 229-240.

Thöle, H., Gaedicke, C., Kuhlmann, G., Reinhardt, L., 2014. Late Cenozoic sedimentary evolution of the German North Sea – A seismic stratigraphic approach. Newsletter on Strat., 1-31.

Turrell, W.R., Slesser, G., Adams, R.D., Payne, R., Gillibrand, P.A., 1999. Decadal variability in the composition of Faroe-Shetland Channel bottom water. Deep-Sea Res. 46, 1-25.

van der Vegt, P., Janszen, A., Moscariello, A., 2012. Tunnel valleys: current knowledge and future perspectives. Geol. Soc., London, Spec. Publ. 368, 75-97.

Vaughan-Hirsch, D.P., Phillips, E.R., 2017. Mid-Pleistocene thin-skinned glaciotectonic thrusting of the Aberdeen Ground Formation, Central Graben region, central North Sea. J. Quat. Sci. 32, 196-212.

Westaway, R., 2017. Isostatic compensation of Quaternary vertical crustal motions: coupling between uplift of Britain and subsidence beneath the North Sea. J. Quat. Sci. 32, 169-182.

Westerhoff, W., 2009. Stratigraphy and sedimentary evolution: the lower Rhine-Meuse system during the Late Pliocene and Early Pleistocene (southern North Sea Basin). PhD Dissertation, University of Amsterdam. Geol. Survey Netherlands.

White, N., Lovell, B., 1997. Measuring the pulse of a plume with the sedimentary record. Nature, 387, 888-891.

Woodworth-Lynas, C.M-T, Josenhans, H.W., Barrie, J.V., Lewis, C.F.M., Parrott, D.R., 1991. The physical processes of seabed disturbance during iceberg grounding and scouring. Cont. Shelf Res. 11, 939-961.

Zagwijn, W.H., 1985. An outline of the Quaternary stratigraphy of the Netherlands. Geol. Mijnb. 64, 17-24.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe. Geol. Soc. London.

Ziegler, P.A., 1992. North Sea rift system. Tectonophysics, 208, 55-75.

Figure captions

Figure 1. (a) Location map of the North Sea. Red lines are national boundaries. Dotted blue line is approximate 500 m depth contour of the base-Quaternary, showing the shape of the infilled North Sea basin. Dotted black line shows where the base-Quaternary surface is truncated by the Upper Regional Unconformity (URU). In the Danish and southernmost Norwegian sectors, this truncation surface corresponds with the transition zone from

conformable to erosive base-Quaternary of Nielsen et al. (2007). Orange lines locate seismic lines shown in Figs. 5 to 8. DB = Dogger Bank; DK = Denmark; GE = Germany; NL = Netherlands; MP = Måløy Plateau; OI = Orkney Islands; SI = Shetland Islands. WB = Witch Ground Basin. (b) Map showing the coverage of 2D and 3D seismic data used in this study. Green areas are 3D seismic cubes. Black dashed line is present-day shelf break.

Figure 2. Table showing correlation between stratigraphic frameworks. Solid and dashed lines are well-constrained and poorly-constrained ages, respectively. Question marks show URU-equivalent surface in the southern and central North Sea. CL = Clinoform Unit; Ja = Jaramillo; Mio = Miocene. Red lines are major seismo-stratigraphic surfaces shown in Fig. 3. Blue lines are minor seismo-stratigraphic surfaces for the southern and central North Sea sub-basin, shown in Fig. 9. Note that many of the early- and mid- Quaternary units in the northern and central North Sea are not present at any significant thickness in the southern North Sea.

Figure 3. Time structure maps showing the morphology of major seismo-stratigraphic surfaces in the North Sea. Dashed blue line is western flank of the Norwegian Channel. Dashed black line shows where the base-Quaternary surface is truncated by the Upper Regional Unconformity (URU). Contours are 100 ms. Red lines are national boundaries. Dashed grey line is present-day shelf break. TWT = two-way travel time. (a) base-Quaternary surface of 2.6-2.75 Ma. (b) Top of Unit B surface (tentatively suggested as 1.6-1.7 Ma). (c) URU and URU-equivalent surface. This is a time-transgressive surface that may be as old as 1.1 Ma to the northeast of the study area and as young as 0.5 Ma to the south. (d) Present-day seafloor. DB = Dogger Bank. MP = Måløy Plateau; WB = Witch Ground Basin.

Figure 4. Isopach maps showing the infill of the North Sea Basin. (a) Sediment thickness between the base-Quaternary surface and the present-day seafloor. Dashed black line shows where the base-Quaternary surface is truncated by the Upper Regional Unconformity (URU). (b) Sediment thickness between the base-Quaternary surface and the top of Unit B surface (2.6 – *c.*1.7/1.6). (c) Sediment thickness between the top of Unit B surface and the URU and URU-equivalent surface. (d) Sediment thickness between the URU and URU-equivalent surface and the present-day seafloor. Contours are 100 ms. Red lines are national boundaries. Dashed black line is present-day shelf break. TWT = two-way travel time. MP = Måløy Plateau.

Figure 5. (a) NW-SE 2D seismic profile across the central North Sea Basin (Courtesy TGS). Location is shown in Fig. 1a. Vertical exaggeration = 70. (b) Interpretation of the profile shown in (a). CL = Clinoform Unit; TCB = top Central Basin Unit; UCB = top Upper Central Basin Unit. Colours match those used in Fig. 11. TWT = two-way travel time.

Figure 6. NE-SW 2D seismic profile across the southern North Sea Basin (Courtesy TGS). Location is shown in Fig. 1a. Vertical exaggeration = 85. (b) Interpretation of the profile shown in (a). CL = Clinoform Unit. Colours match those used in Fig. 11. TWT = two-way travel time.

Figure 7. NW-SE 2D seismic profile across the northernmost central North Sea Basin (Courtesy TGS). Location is shown in Fig. 1a. Vertical exaggeration = 85. (b) Interpretation of the profile shown in (a). CL = Clinoform Unit; TCB = top Central Basin Unit; UCB = top Upper Central Basin Unit. Colours match those used in Fig. 11. TWT = two-way travel time.

Figure 8. NW-SE 2D seismic profile across the northern North Sea Basin (Courtesy TGS). Location is shown in Fig. 1a. Vertical exaggeration = 40. (b) Interpretation of the profile shown in (a). C marks the location of contourite lenses within Unit C, as described in Batchelor et al. (2017). TWT = two-way travel time.

Figure 9. Time structure maps showing the morphology of Early Quaternary seismo-stratigraphic surfaces in the southern and central North Sea sub-basin. Contours are 100 ms. Red lines are national boundaries. (a) base-Quaternary surface of *c.*2.6 Ma. Dashed black line shows where the base-Quaternary surface is truncated by the Upper Regional Unconformity (URU). (b) Top of Sequence 9 surface of *c.*2 Ma. (c) Top of Sequence 12 surface of *c.*1.9 Ma. (d) Top of Sequence 13 surface, which is younger than 1.8 Ma (Kuhlmann and Wong, 2008). (e) Top of Clinoform Unit 1 surface. (f) Top of Clinoform Unit 2 surface. (g) Top of Clinoform Unit 3 surface. Black arrow is location of elongate ridges interpreted as mega-scale glacial lineations in this study (Fig. 12c). Red arrows show location of elongate ridges interpreted as mega-scale glacial lineations by Buckley (2012, 2016) and Rose et al. (2016). (h) Top of Central Basin Unit. (i) Top of Upper Central Basin Unit (URU equivalent).

Figure 10. Isopach maps showing the Early Quaternary sedimentary infill of the southern and central North Sea sub-basin. Contours are 100 ms. Red lines are national boundaries. (a)

base-Quaternary to the top of Sequence 5 (Sequences 1-5). (b) Top of Sequence 5 to top of Sequence 9 (Sequences 6-9). (c) Top of Sequence 9 to top of Sequence 12 (Sequences 10-12). (d) Sequence 13. (e) Clinoform Unit 1. (f) Clinoform Unit 2. (g) Clinoform Unit 3. (h) Central Basin Unit. (i) Upper Central Basin Unit.

Figure 11. Schematic map showing the distribution of Quaternary seismo-stratigraphic units within the North Sea Basin, produced from the 500 ms time interval. Colours match those used in Figs. 5-8. Pink areas are deltas. Vertical hatching shows contouritic units. Dashed blue line is approximate 500 m depth contour of the base-Quaternary. Dashed black line shows where the base-Quaternary surface is truncated by the Upper Regional Unconformity (URU). Grey dashed line is present-day shelf break.

Figure 12. Examples of features identified using cubes of 3D seismic data from the North Sea. Locations are shown in Fig. 1a. (a) Amplitude map showing slope-parallel mounded ridges, interpreted as silt/sand ridges formed by contour currents, on a palaeo-slope horizon within Clinoform Unit 1 in the central North Sea. (b) Time slice through an amplitude cube of iceberg ploughmarks on a palaeo-shelf within Clinoform Unit 1 in the central North Sea. (c) Time slice through an amplitude cube of northeast-southwest orientated elongate ridges, interpreted as mega-scale glacial lineations (MSGLs), on the top of Clinoform Unit 3 surface in the central North Sea (Fig. 9g). N-S lines are noise from acquisition direction. (d) Time slice through an amplitude cube of a linear to curvilinear wide channel, interpreted as a tunnel valley, within mid- to late-Quaternary sediments in the central North Sea. (e) Amplitude map showing elongate lobes on a palaeo-slope horizon within Unit D in the northern North Sea, which are interpreted as glacigenic debris-flows. (f) Time slice showing curvilinear ridges and depressions within Unit D in the northern North Sea, which are interpreted as detached slide blocks.

Figure 13. Overview schematic maps of basin morphology and processes of sedimentation in the North Sea Basin at four time steps through the Quaternary. (a) earliest Quaternary (b) top of Unit B surface, of around 1.7-1.6 Ma. (c) Middle Pleistocene Transition, around 1 Ma. (d) Elsterian glaciation of MIS 12, around 0.5 Ma. The ice-sheet limit is also shown during MIS 6 and the Last Glacial Maximum (LGM). Ice-sheet extents are from Gibbard and Clark (2011). Blue lines show locations of major rivers. Purple lines show delivery of glacial sediment. Orange dashed lines show suggested direction of water circulation in the basin.

Brown lines are downslope gullies. Pink lines are iceberg ploughmarks. Orange lines are ridges produced by contour currents. Pink arrows show ice-flow directions. WA = Weald-Artois bedrock ridge.

Table 1. Estimated volume of major Quaternary units in the North Sea (52°N - 62°N), including the southern and central sub-basin and the northern sub-basin, within the 500 m contour of the base-Quaternary surface. Note that the northern sub-basin does not include the North Sea TMF. An average interval velocity of 1800 m/s was used for depth conversion.

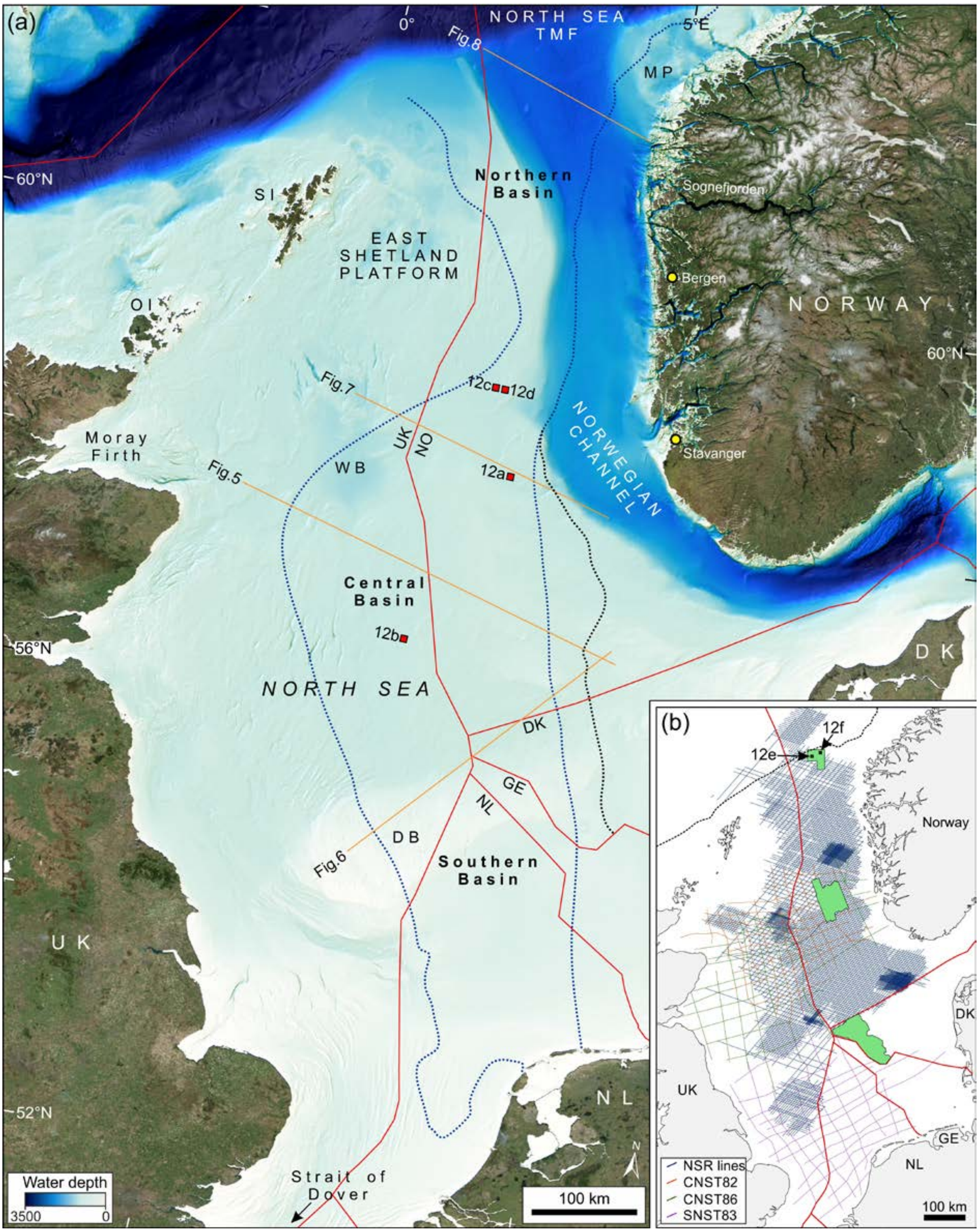

(a)
0°
NORTH SEA
TMF
5°E
Fig.8
MP
60°N
SI
Northern
Basin
Sognefjorden
EAST
SHETLAND
PLATFORM
OI
Bergen
NORWAY
60°N
Fig.7
12c
12d
Moray
Firth
UK
NO
NORWEGIAN
CHANNEL
Stavanger
WB
12a
Fig.5
Central
Basin
12b
56°N
DK
NORTH SEA
DK
GE
NL
DB
Fig.6
Southern
Basin
UK
52°N
NL
Water depth
3500
0
Strait of
Dover
100 km
(b)
12f
12e
Norway
DK
UK
GE
NL
NSR lines
CNST82
CNST86
SNST83
100 km

Figure 1

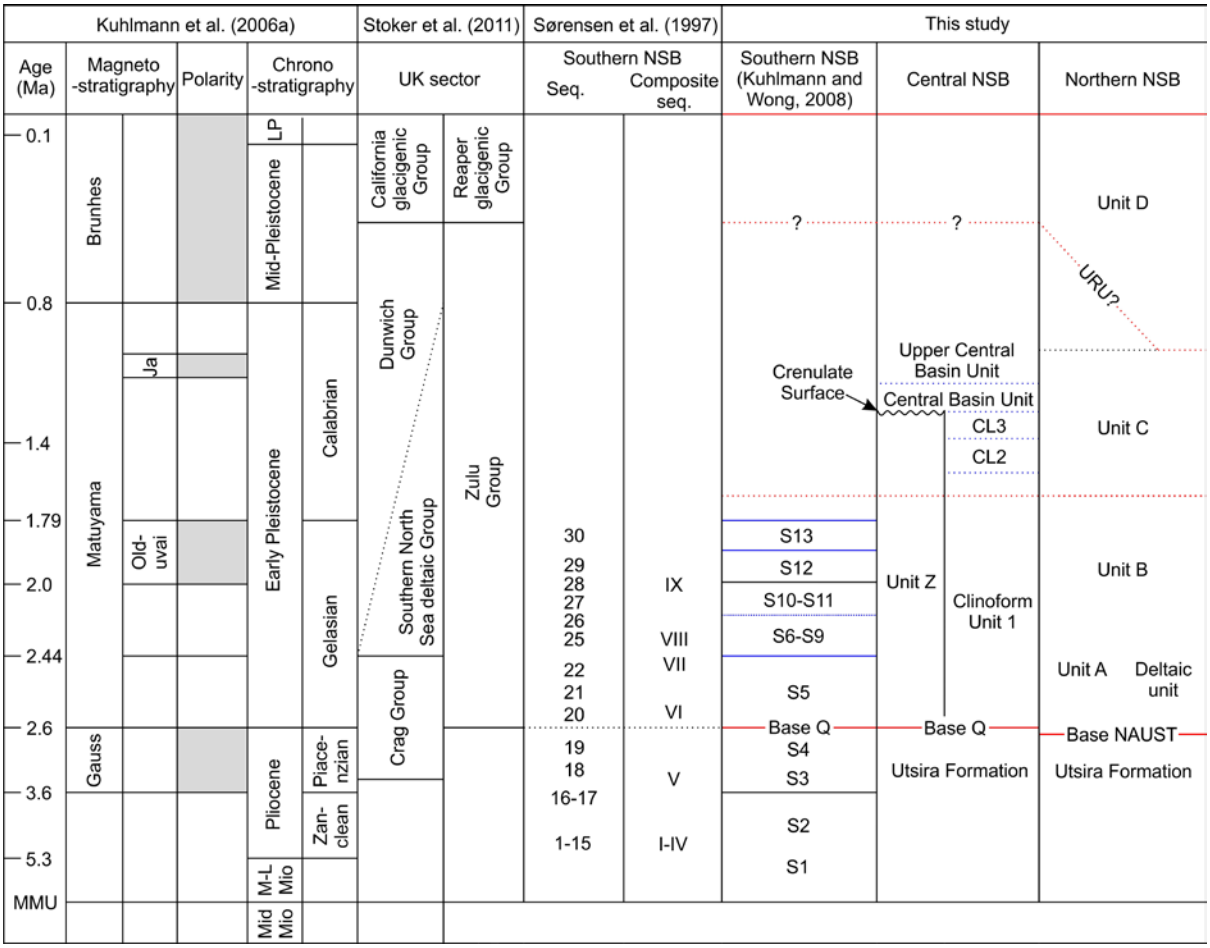
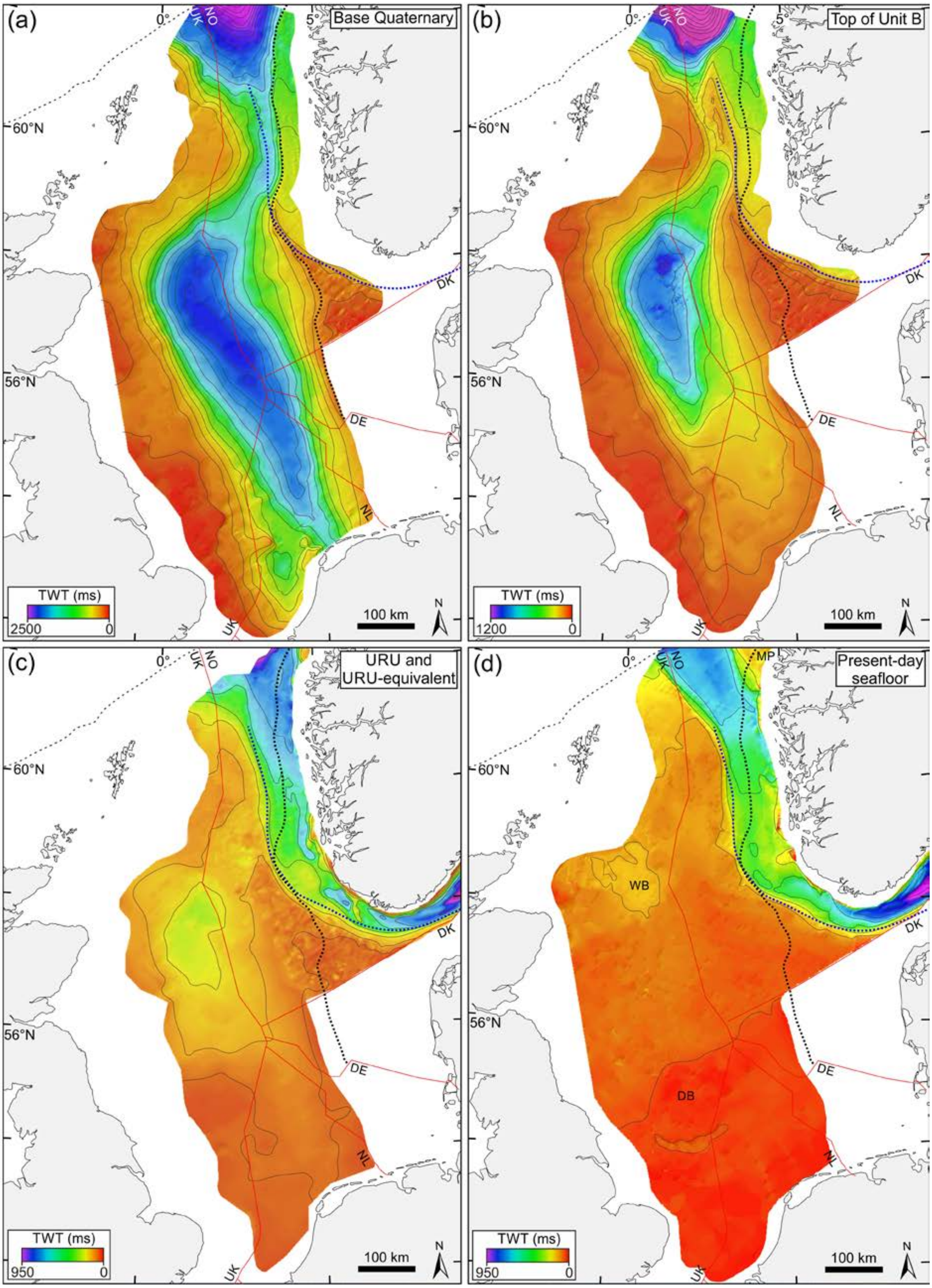

Kuhlmann et al. (2006a)
Stoker et al. (2011)
Sørensen et al. (1997)
This study
Age (Ma)
Magneto -stratigraphy
Polarity
Chrono -stratigraphy
UK sector
Southern NSB
Seq.
Composite seq.
Southern NSB (Kuhlmann and Wong, 2008)
Central NSB
Northern NSB
0.1
0.8
1.4
1.79
2.0
2.44
2.6
3.6
5.3
MMU
Brunhes
Matuyama
Gauss
Ja
Old-uvai
LP
Mid-Pleistocene
Early Pleistocene
Pliocene
M-L Mio
Mid Mio
Calabrian
Gelasian
Piace-nzian
Zan-clean
California glacigenic Group
Reaper glacigenic Group
Dunwich Group
Southern North Sea deltaic Group
Zulu Group
Crag Group
30
29
28
27
26
25
22
21
20
19
18
16-17
1-15
IX
VIII
VII
VI
V
I-IV
?
S13
S12
S10-S11
S6-S9
S5
Base Q
S4
S3
S2
S1
Crenulate Surface
Upper Central Basin Unit
Central Basin Unit
CL3
CL2
Unit Z
Clinoform Unit 1
Utsira Formation
Unit D
URU?
Unit C
Unit B
Unit A
Deltaic unit
Base NAUST

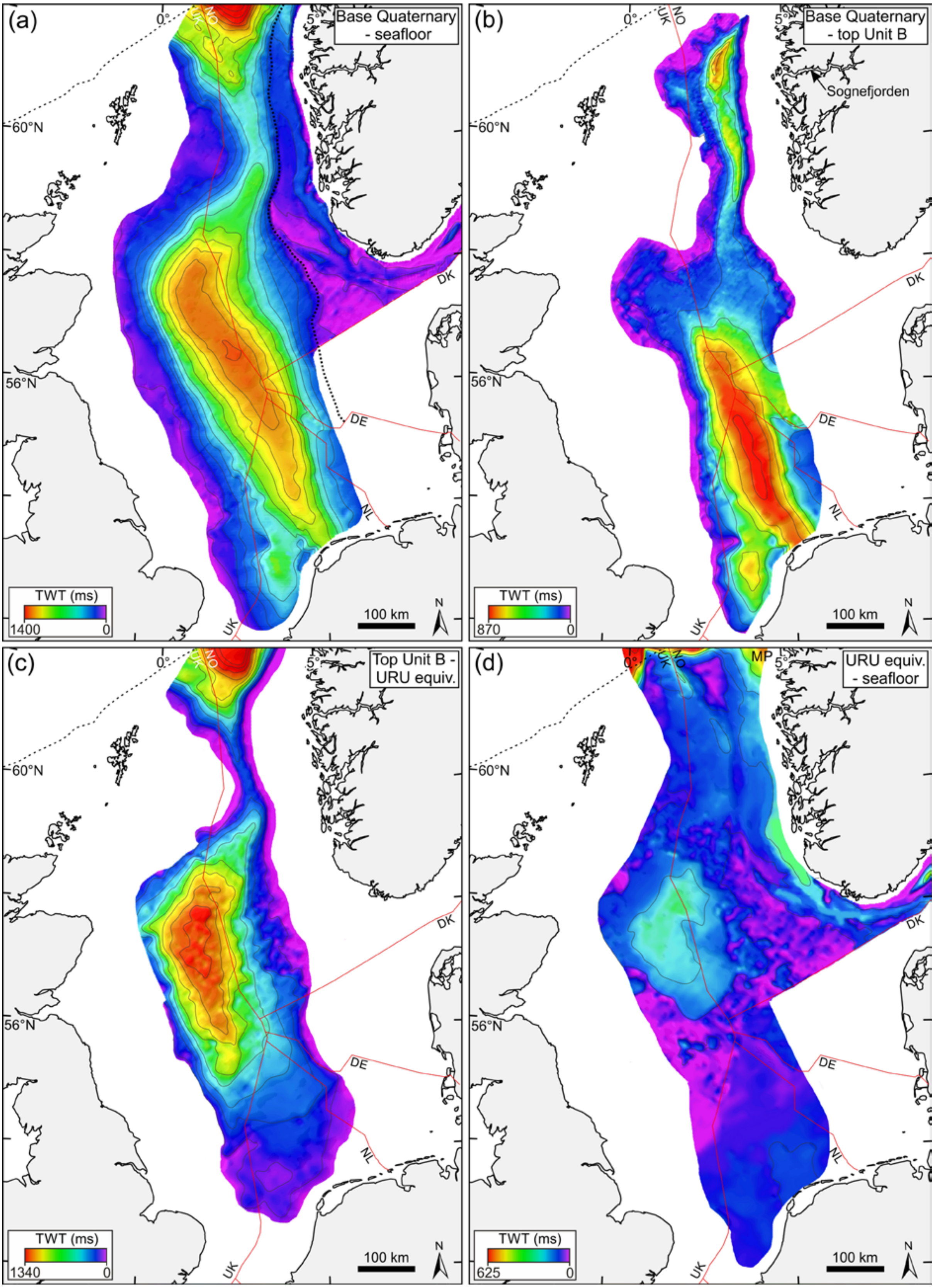
Figure 2



1493

1494 Figure 3

1495



1496

1497 Figure 4

1498

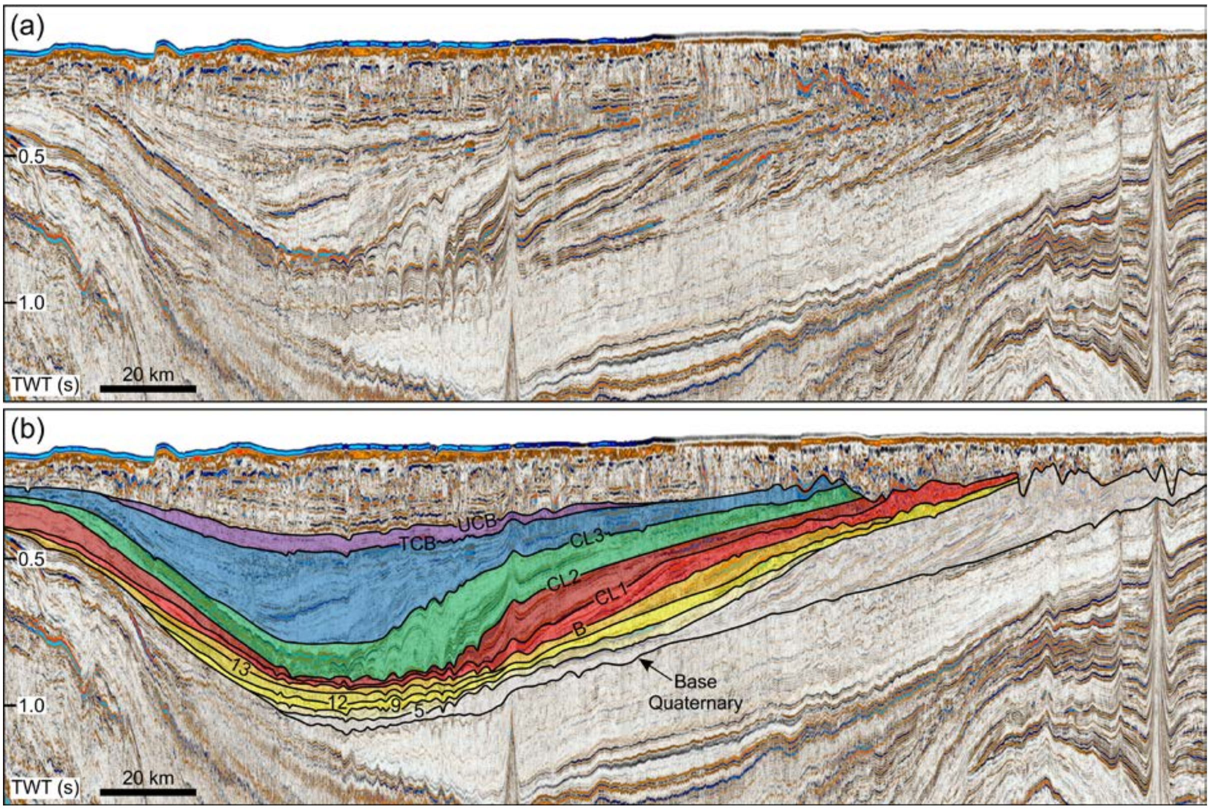

(a)
0.5
1.0
TWT (s)
20 km
(b)
UCB
TCB
CL3
CL2
CL1
B
13
12
9
5
0.5
1.0
Base
Quaternary
TWT (s)
20 km

Figure 5

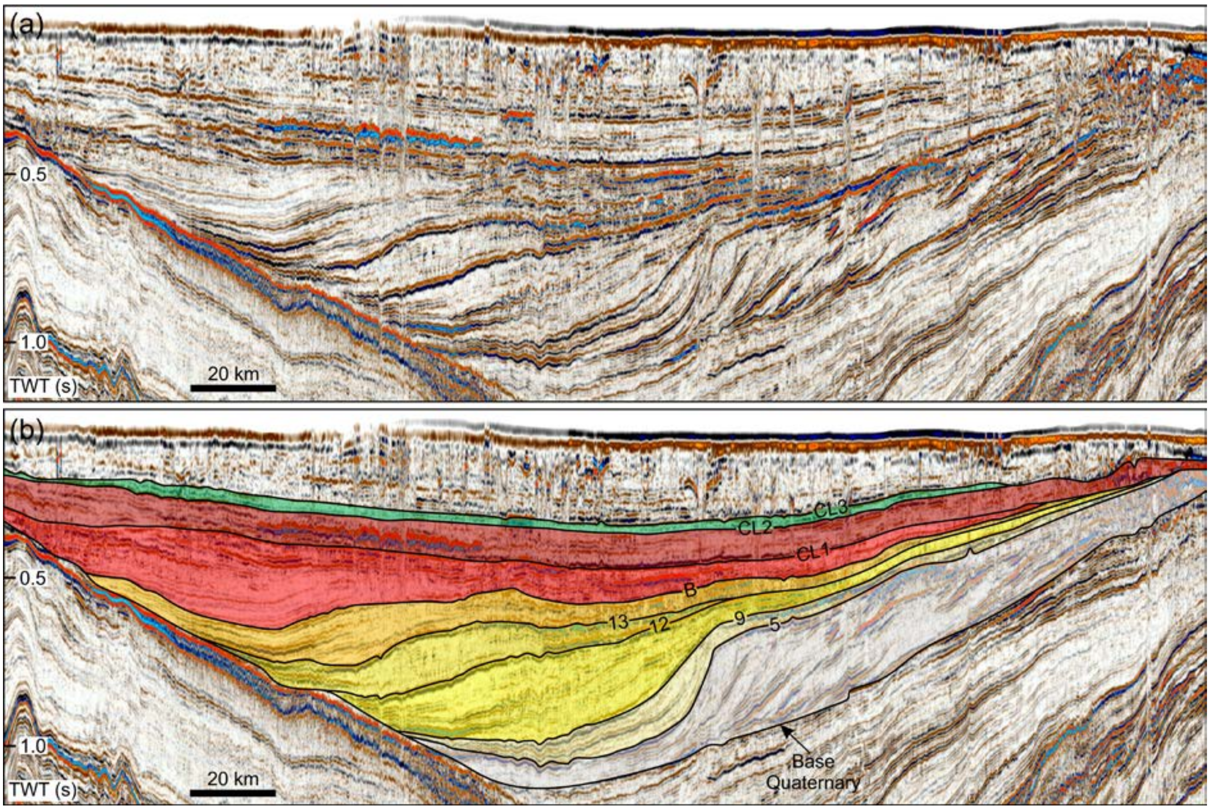
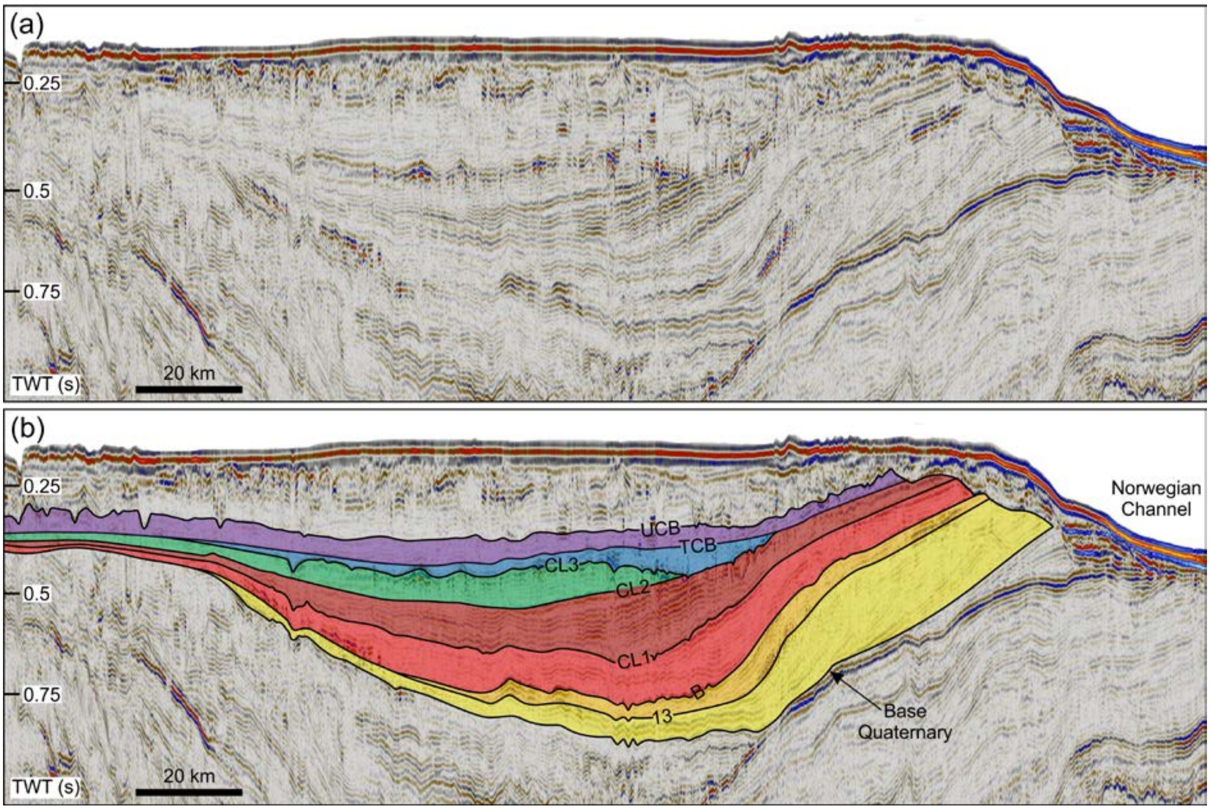

(a)
0.5
1.0
TWT (s)
20 km
(b)
CL3
CL2
CL1
B
13
12
9
5
0.5
1.0
TWT (s)
20 km
Base Quaternary

Figure 6



1505

1506 Figure 7

1507

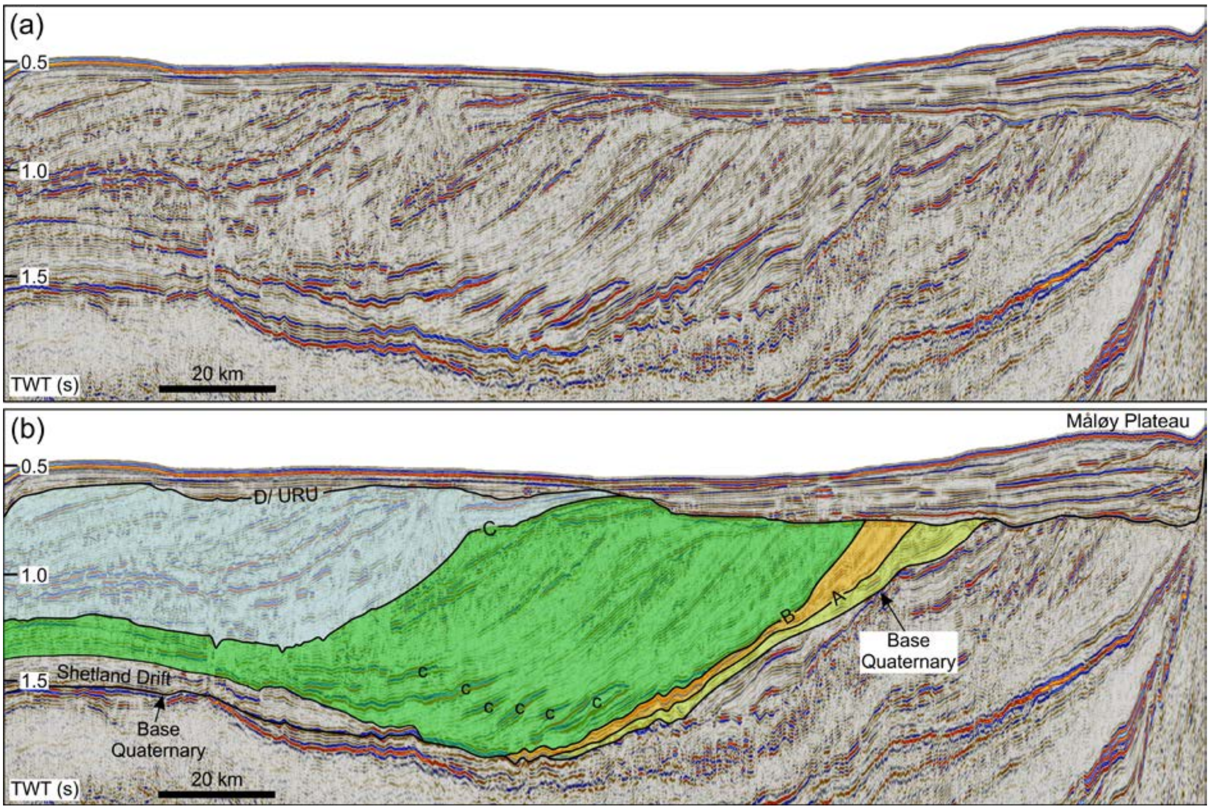

(a)
0.5
1.0
1.5
TWT (s)
20 km
(b)
Måløy Plateau
0.5
D/ URU
C
1.0
B
A
Base
Quaternary
1.5
Shetland Drift
c
c
c
c
c
c
Base
Quaternary
TWT (s)
20 km

Figure 8

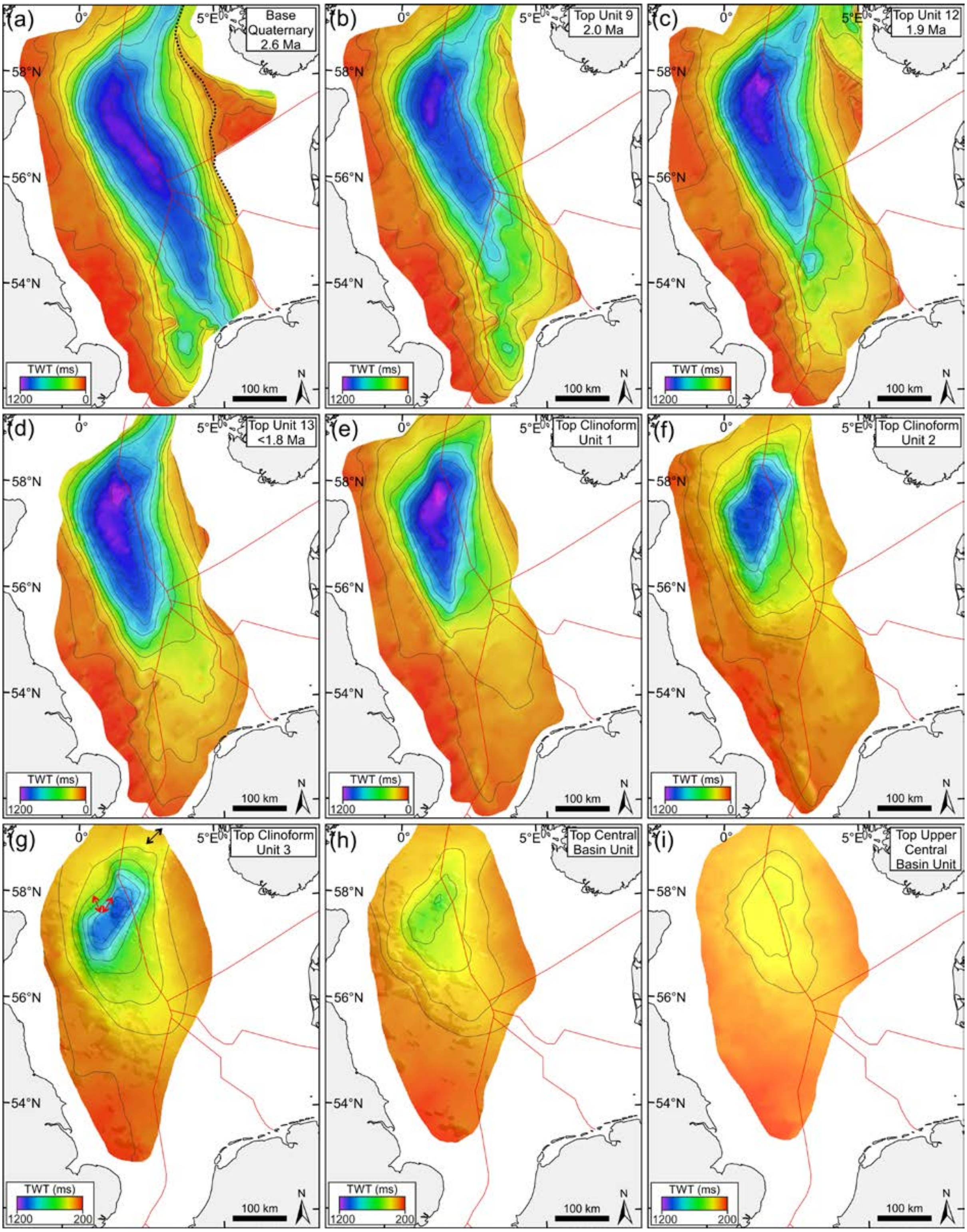

(a)
Base Quaternary 2.6 Ma
(b)
Top Unit 9 2.0 Ma
(c)
Top Unit 12 1.9 Ma
(d)
Top Unit 13 <1.8 Ma
(e)
Top Clinoform Unit 1
(f)
Top Clinoform Unit 2
(g)
Top Clinoform Unit 3
(h)
Top Central Basin Unit
(i)
Top Upper Central Basin Unit
0°
5°E
58°N
56°N
54°N
TWT (ms)
1200
0
200
100 km
N

Figure 9

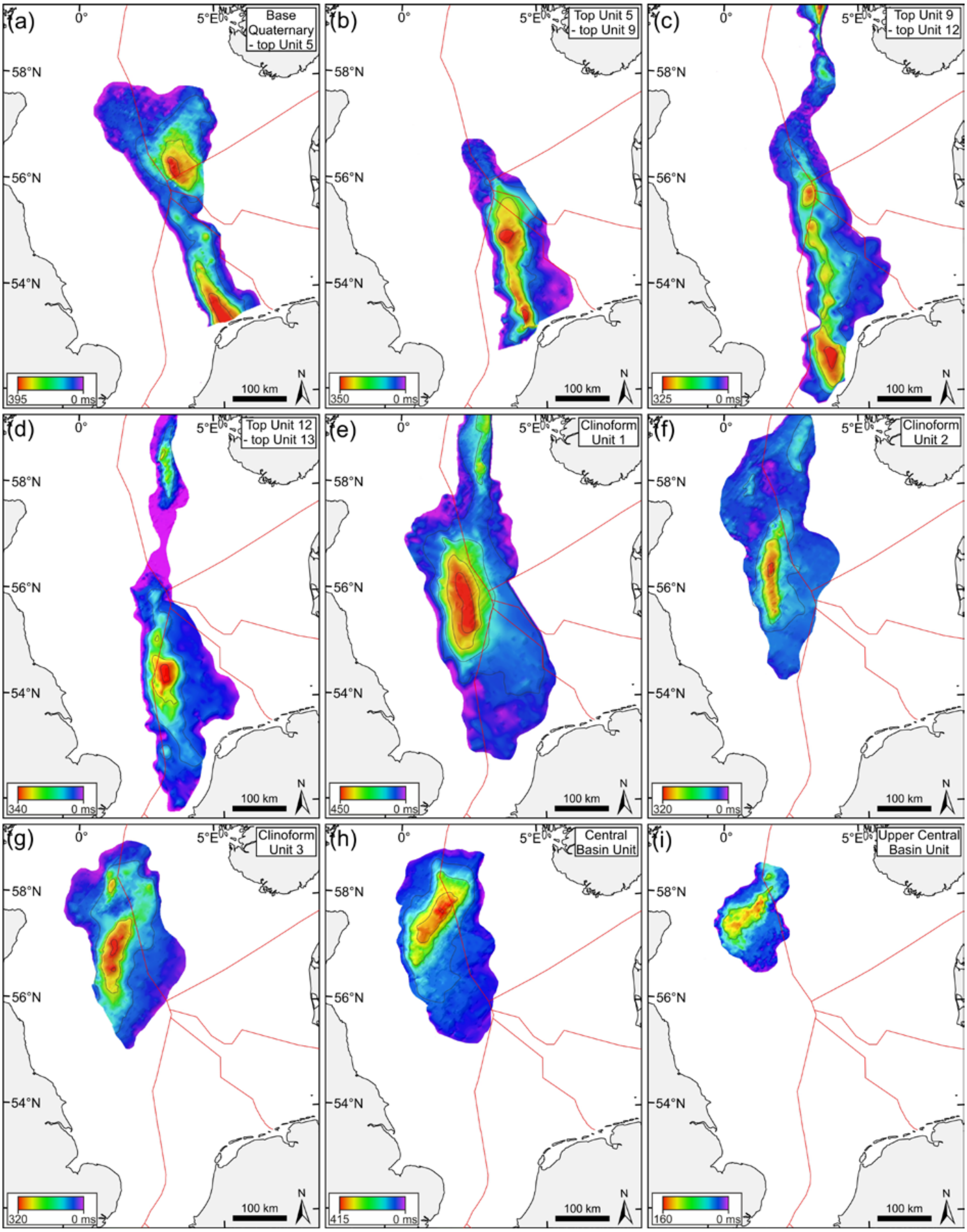

(a)
Base Quaternary - top Unit 5
395
0 ms
(b)
Top Unit 5 - top Unit 9
350
0 ms
(c)
Top Unit 9 - top Unit 12
325
0 ms
(d)
Top Unit 12 - top Unit 13
340
0 ms
(e)
Clinoform Unit 1
450
0 ms
(f)
Clinoform Unit 2
320
0 ms
(g)
Clinoform Unit 3
320
0 ms
(h)
Central Basin Unit
415
0 ms
(i)
Upper Central Basin Unit
160
0 ms
0°
5°E
58°N
56°N
54°N
100 km
N

Figure 10

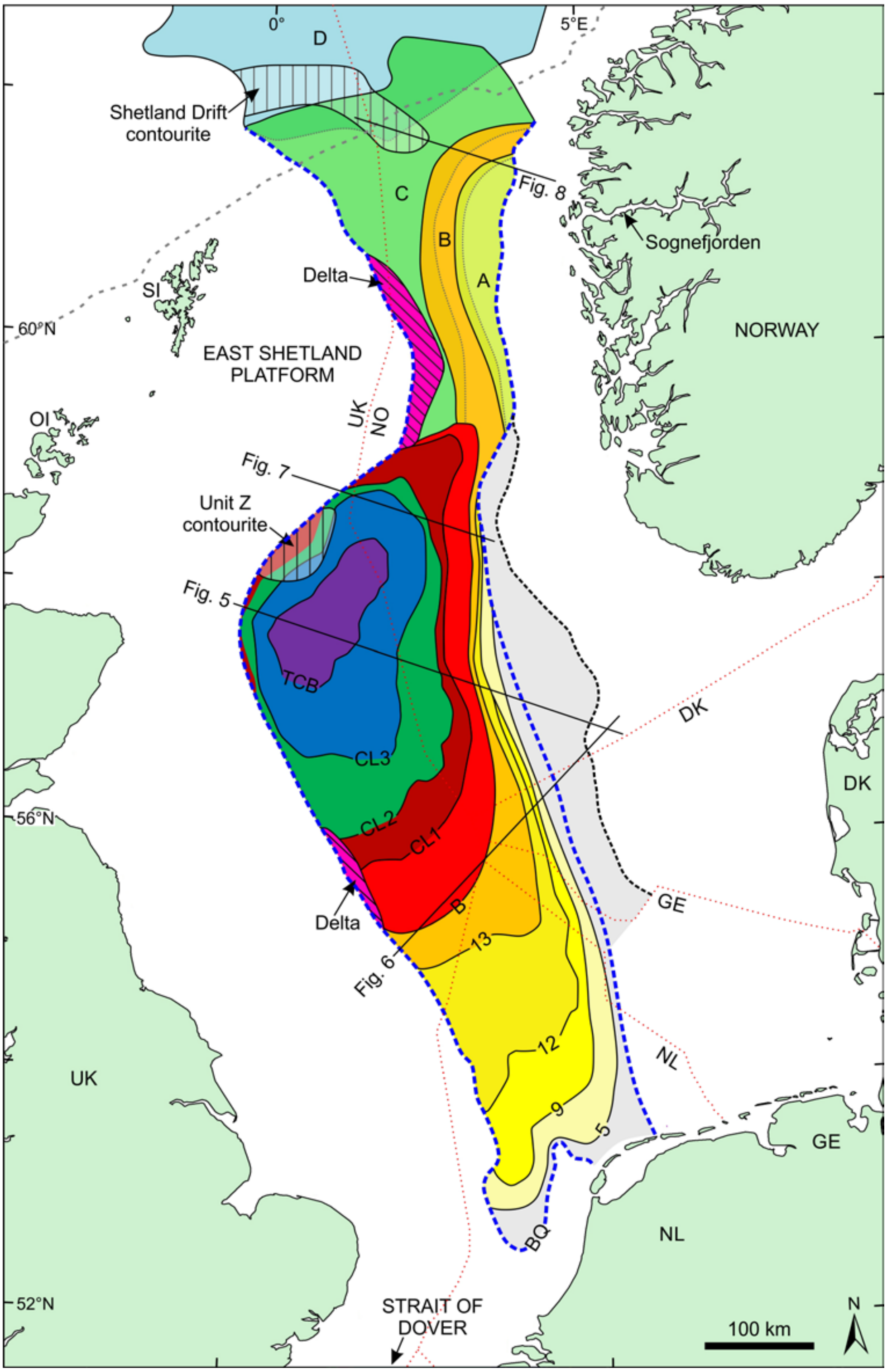

0°
5°E
D
Shetland Drift
contourite
C
Fig. 8
B
A
Sognefjorden
Delta
SI
60°N
EAST SHETLAND
PLATFORM
NORWAY
OI
UK
NO
Fig. 7
Unit Z
contourite
Fig. 5
TCB
CL3
CL2
CL1
DK
DK
56°N
GE
Delta
B
13
Fig. 6
12
NL
UK
9
5
GE
BQ
NL
52°N
STRAIT OF
DOVER
100 km
N

Figure 11

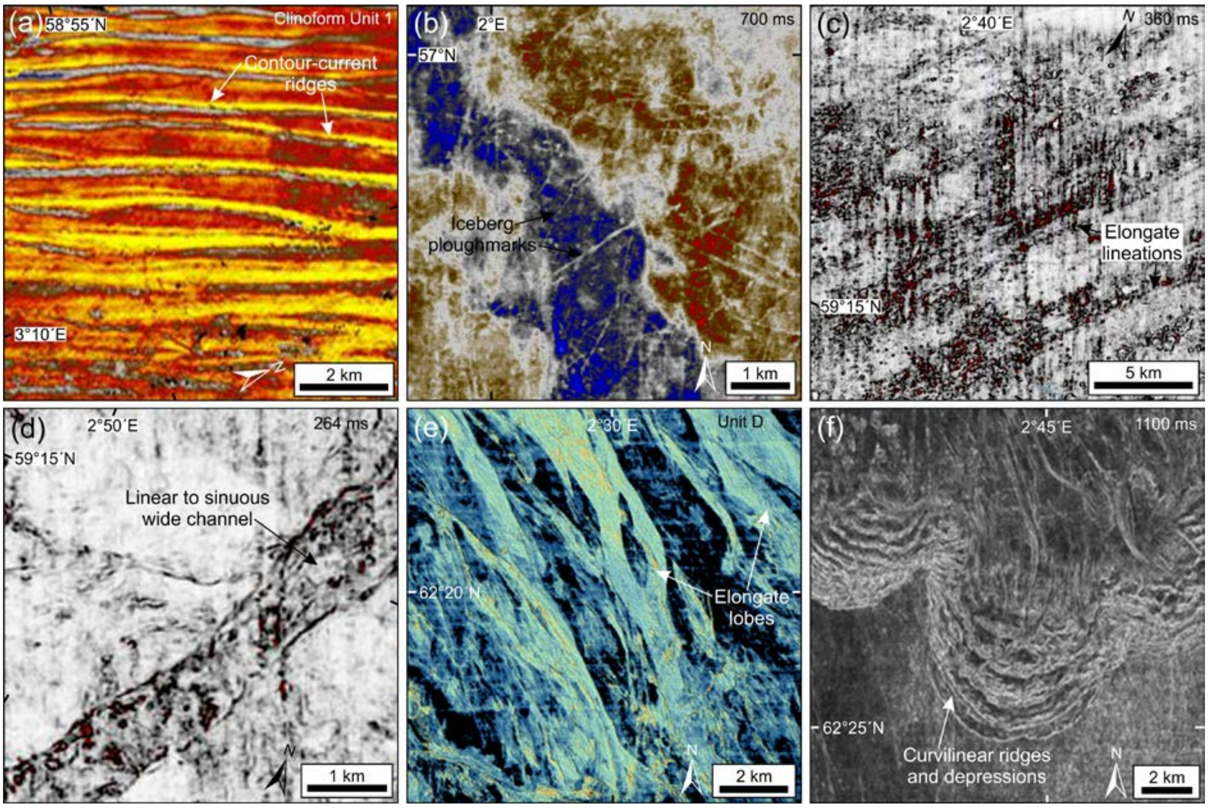
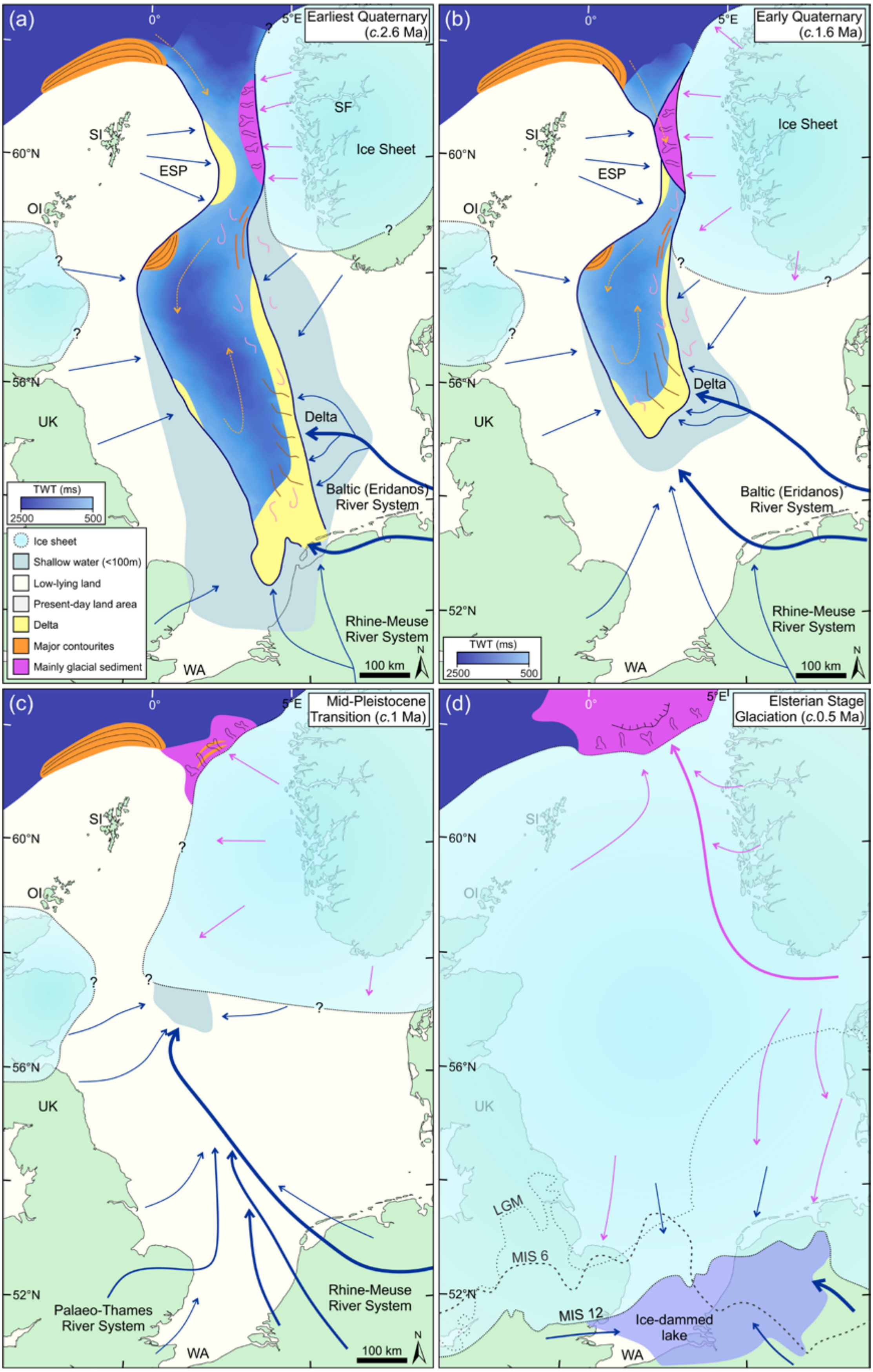

(a)
58°55´N
Clinoform Unit 1
Contour-current ridges
3°10´E
2 km
(b)
2°E
700 ms
57°N
Iceberg ploughmarks
1 km
(c)
2°40´E
N
360 ms
Elongate lineations
59°15´N
5 km
(d)
2°50´E
264 ms
59°15´N
Linear to sinuous wide channel
N
1 km
(e)
2°30´E
Unit D
62°20´N
Elongate lobes
N
2 km
(f)
2°45´E
1100 ms
62°25´N
Curvilinear ridges and depressions
N
2 km

Figure 12



1524

1525 Figure 13